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THE "AKULE" FISHERY OF HAWAII

By

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The fisheries of Hawaii are typical of many island fisheries, in that they are characterized by relatively low productivity and high species diversity. The majority of the species fished are not conducive to large commercial operations, but are nevertheless important to the economy of the islands.

The Hawaiian fish fauna is reported to number 682 species (R. T. B. Iversen, Southeast Region, National Marine Fisheries Service, NOAA, Honolulu, HI 96812, pers. commun.), but fewer than 50 species contribute to the bulk of the commercial fish catch.¹ Of these, the akule, Trachurops crumenophthalmus, ranks second only to the tunas and billfishes in annual landings. During the years 1970 to 1975, akule landings accounted for approximately 38% of the reported commercial fish catch (not including tunas and billfishes). By commercial standards, the akule fishery is a relatively small fishery, highly dependent on local supply and demand. Since 1951, the annual catch has fluctuated from a low of 68,329 kg (68.4 metric tons) in 1963 to an alltime high of 444,482 kg (201.7 metric tons) in 1970. (Figure 1).

The following report briefly describes the biology of the species, fishing methods, preservation and marketing, protection, and management.

BIOLOGY

Vernacular Names

Ature, Aturepai	Cook Islands
Ature, Aramea, Orare	Tahiti
Otule	Tonga
Otule	Samoa
Buma	Solomons
Torro	New Guinea (Port Moresby)
Meaji	Japan

In the Americas, this fish is more commonly referred to as bigeye scad. In Hawaii, various names have been given to this fish at different sizes. Small fish of 5.1-7.6 cm (2-3 in.) in length are known as paa'a, the intermediate sizes as hahalalu, and fish greater than 22.8 cm (9 in.) as akule (Pukui and Elbert 1957).

¹Commercial fish catch by species. State of Hawaii, Department of Land and Natural Resources, Division of Fish and Game, Honolulu, Hawaii.

The akule is circumtropically distributed in the warm coastal waters of the Atlantic, Indian, and Pacific Oceans. In Hawaiian waters, the akule ranges throughout the Hawaiian archipelago from Kure Island to the island of Hawaii. The akule inhabits the coastal waters of all the islands, from the shallow shoreline out to depths of 100 m (50 fathoms), and is relatively scarce in offshore waters. Tagging results obtained by the State of Hawaii, Division of Fish and Game indicate that the majority of akule tended to remain in the proximity of the area of release.

The akule is a relatively fast growing fish. After the first year it measures about 229 mm, and in 2 years the akule grows to approximately 305 mm in length (Gosline and Brock 1960). The size at which the female akule reaches sexual maturity and begins spawning was determined by Kawamoto (1973) to be about 235 to 250 mm FL (fork length). The males mature at about 220 to 230 mm FL. The ovaries are predominantly mature or in spent condition during the months of April through November, indicating that spawning occurs during this period. The presence of schools of young fish under 152 mm in late August suggests that peak spawning occurs during the spring and early summer months.

"According to growth estimates, hahalalu appear in our inshore waters from 150 mm FL, or 4 months after hatching. The bulk of akule caught by the commercial fishery range in size from 210 to 265 mm making them between 8 and 18 months old." (Kawamoto 1973.)

FISHING METHODS

The present commercial akule fisheries are conducted by two principal methods: handline and "surround" net. Although this report deals with their application to the akule fishery, the methods described are also utilized to catch a number of other species.

The handline method involves fishing from a vessel at night utilizing a light to attract the fish. This method depends on the phototactic response of food organisms to light which in turn attract the akule. As such, the best fishing results are obtained by fishing during the dark phase of the moon with a suitable source of light.

Powell (1968) describes in detail the akule night-fishing method. Night fishing is generally conducted in inshore waters to a depth of 100 m (50 fathoms). Akule are hooked usually at depths from the surface to 10 m (5 fathoms).

The handlines are constructed of lightweight material with three to five baited hooks or artificial lures. In bait fishing, small anchovy or chum made of finely ground fish is first released to attract and excite the akule into taking the baited hooks. In fishing with lures, the small lures (fly) are continuously lowered and raised at a steady

pace in order to mimic the movement of plankton or small fish in the water. Nightly catches average 18.1 to 22.7 kg (40 to 50 lb) per boat but occasional catches may exceed 45.4 kg (100 lb). The lure method is more commonly used because of its simplicity. Bait fishing is at times reverted to when lure fishing is poor.

Historically, surround nets were restricted in use to the relatively shallow shoreline waters. Schools of fish were sighted from high grounds on land or from atop trees. The "spotter" coordinated the net setting operation by hand signals to the fishermen.

With the introduction of fish spotting from airplanes and the use of scuba diving gear, the net fishery has greatly increased its operational efficiency. Presently, the net fishery is composed of small vessels operating daily in waters relatively close to land and some larger vessels having long-range capabilities and equipped with brine chill refrigeration system and purse seine power block. The larger vessels possess multispecies fishing capability.

The surround-net fishery utilizes two types of net: bag net (akule net) and gill net. The nets are variable in design according to species of fish to be caught and the habitat to be exploited. Basically, the nets are panels with a float line and a lead line. The weights are heavy enough to take the net to the bottom but not too heavy as to make it difficult to retrieve. The floats are sufficiently large to keep the net upright, without lifting the net off the bottom. Both nets are set in water deeper than the depth of the net.

The bag net is a combination bag and seine net constructed from nylon webbing of 3.8 cm mesh. The bags commonly in use measure about 16 m (48 ft) long with a mouth opening of 12 to 16 m (36 to 48 ft) in width. The height of the bag varies with the depth of the seine net used. The seine portion is formed by sections of net each 100 m (300 ft) long and varying in depth from 12 to 26 m (36 to 78 ft). The desired length of net is derived by lacing sections together and can be as much as 1,000 m (3,000 ft) in length. The depth of the net used is determined by the depth of water. Although present nets fish depths down to 33 m (99 ft) the depth of the water where the bag is attached does not exceed the bag depth.

The setting pattern depends upon the behavior of the fish school, depth of water, and current condition during the fishing operation. A skiff is used in setting the net around a school of fish. The two ends of the net are overlapped to completely encircle the fish. Divers then enter the water on the down-current end of the net and remove the lacing between the two net sections. A bag is attached in-between the sections and secured by weaving foot-long "chopsticks" through the webbing. The circle of the net is reduced in size by "cutting" and moving sections of net toward the center to direct the surrounded fish into the bag.

After the fish have entered the bag, the sticks are removed while the mouth bottom of the bag is brought to the surface and secured to the vessel. The fish are brailled with nets into refrigerated (ice or brine) holds on the vessel. The seine-net sections are then retrieved manually or with a power block. This method of fishing usually catches most of the fish in a school.

The gill net is constructed from 15 or 18 lb test, 6.3 cm (2.5 in.) mesh monofilament webbing. Blue monofilament is preferred because of its relative transparency in local waters. The more commonly used nets are 1.7 to 3.3 m (5 to 10 ft) in depth, with a section ranging from 42 to 100 m (126 to 300 ft) in length. The complete net is composed of several sections laced together and can be as long as 1,000 cm (3,000 ft).

Gill nets are utilized in depths to 12 m (36 ft) in areas of rough terrain. As gill nets are light and portable, land operations have developed in which the skiffs are hauled by trucks to locations close to the fish school.

Following setting directions provided by the airplane spotter, the net is set around a fish school by fishermen in skiffs. When the net is set, divers with a skiff enter the water to frighten the fish. Akule instinctively move down and outwards, thereby hitting the net and entangling themselves. The net is retrieved and iced down completely without removing the fish. The fish is removed after returning to shore. A smaller proportion of the fish is usually caught by the gill net method as many escape over the net and the larger meshes selectively gill only the larger fish.

PRESERVATION AND MARKETING

The preservation and marketing of fish in the islands are regulated by consumer preference for fresh fish. The bulk of the commercially caught akule is "iced" and distributed fresh through the auction market.

PROTECTION AND MANAGEMENT

Presently, the akule fishery is managed through two regulations. The first was established in 1929, prohibiting the use of nets with stretch mesh size of less than 38.1 mm (1-1/2 in.). Because of a decrease in catch during the years 1951-65, a second regulation was enacted in 1968 to protect the young akule. The 1968 regulation prohibits the netting of akule under 21.6 cm (8.5 in.) in total length from July through October during the season of peak recruitment into the fishery.

The regulatory measures presently in effect seem to provide adequate protection of the resource as annual landings appear to be holding up at a relatively high level.

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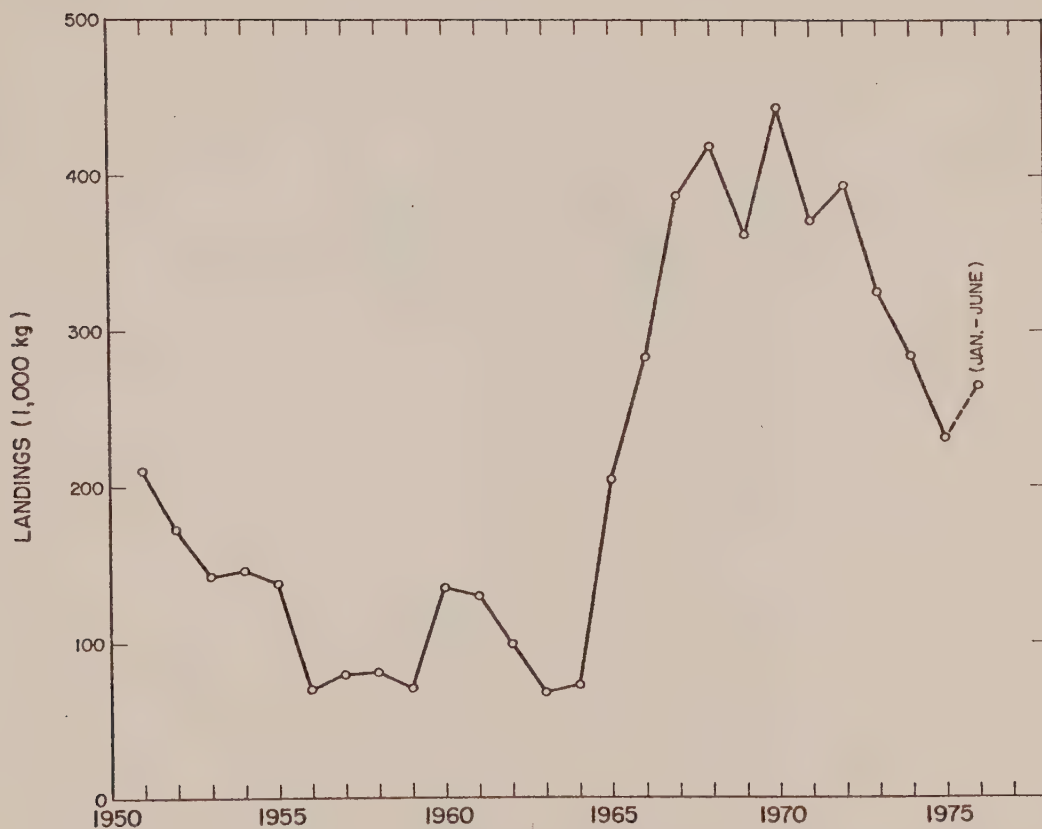


Figure 1.--Hawaii commercial akule landings by years.

A NIGHT HANDLINE FISHERY FOR TUNAS

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An unusual fishery exists in the city of Hilo, Hawaii (population 28.5 thousand). This is the night handline fishery for tunas. As far as I know, the Philippines is the only other place that has a similar fishery (Erling Oswald, South China Sea Fisheries Development and Coordinating Programme, Makati, Rizal, Philippines, pers. commun.). The gear used in the fishery is simple and effective. For that reason this is a type of fishery that would be practical for areas where highly mechanized and expensive methods of fishing are out of reach.

HISTORY

The following account of the origins of the fishery are from interviews of oldtimers in the fishing community of Hilo as written references were not found.

Immigrants from Okinawa are believed to have started the fishery. They went out at night to catch squid as they had done in Okinawa. Occasionally some mysterious denizen of the deep would strike. Upon checking with the native Hawaiians they learned that the strikes were probably made by large tuna. They subsequently equipped themselves with gear to catch the tuna.

The exact year when the fishery started is not known. According to United Japanese Society of Hawaii (1971), the first Okinawans arrived in Hawaii in 1899 to work in the then burgeoning sugar industry. It took another 7 or 8 years, however, for their immigration to reach large numbers. By 1911, 12,000 were living in

Hawaii. Allowing for time to fulfill their contracts with the sugar plantations, I would guess that the fishery for squid started in the second decade of the 1900's.

In the early years of the fishery the boats were powered by sail. In the 1930's up to about 40 motorized boats were involved in the fishery. Until World War II the fishery was primarily for squid. The tunas caught by squid fishermen were known as ika-sibi (squid-tuna in Japanese). The ika-sibi, the name by which the fishery is still called locally, had a reputation for its poor quality as a result of being towed alongside the boat on the way to port. The squid did not require ice and the boats were too small to have the large fish on board. Consequently, these tunas could not compete on the market with the tunas caught on longlines.

The squid fishery stopped abruptly on December 7, 1941, with the Japanese attack on Pearl Harbor. Maritime restrictions prevented boats from fishing at night throughout the duration of World War II.

From the end of the war until 1971, 3-4 boats fished at night for tuna. These boats were equipped with iceboxes to keep the fish in good condition. The fish caught were almost all bigeye tuna, Thunnus obesus. The fishery was limited to these few boats by the market for fresh tuna. The entire catch was sold on the Island of Hawaii, which had a population of 55,000 to 63,000 during that period. By 1971 fresh tuna prices had increased enough to make air shipment of tunas to other markets economical. Since then the night handline fishing fleet has grown to about 30 boats about half of which are part-timers.

GENERAL DESCRIPTION OF FISHERY

Fig. 1

The fishing area is located 15-20 miles (24-32 km) northeast of the port city of Hilo and covers about 50 square miles (129 km^2) (Fig. 1). It is just beyond a marked change in the slope of the bottom. The edge of the shelf appears to be about 365 m deep.

The boats leave port between 4 and 5 p.m. to get to the grounds at sundown. Upon arrival there the engine is turned off and a parachute is attached to the bow and lowered into the water. Two over the surface lights and one underwater light are turned on. Some boats use just the above surface lights and some use just the underwater light but most of them use both types. Typically 25-W and 50-W incandescent bulbs are used for the above surface and underwater lights, respectively. Some fishermen use slightly brighter lights on moonlit nights.

The first fishing operation is to catch the squid, Notodarus hawaiiensis, for bait. Cross-sections of mackerel scad, Decapterus pinnulatus, roughly an inch wide, are used as chum. Squid are caught by angling and gaffing. The hooks are baited with mackerel scad. This is done by cutting off the tail so that the body of the scad is the proper length to fit on the shank of the hook. The shank of the hook is pushed through the length of the fish starting with the cut end and ending at the mouth. A light line attached to the proximal tip of the shank is wound around the fish to keep it from falling apart. This makes it possible to use the same piece of bait repeatedly despite the squid bites that are inflicted upon it. The baited hook is tossed out

about 5 m and slowly pulled back to the boat. In this manner the hook is used not only to hook squid but also to lure the school of squid to within gaffing range of the boat.

A few fishermen prefer to gaff the squid exclusively. In this case a whole scad is hooked through the head with a fish hook. It is tossed out and slowly pulled back to the boat in the same manner applied to the squid hook.

Fishing for tuna begins after 5-10 squid have been caught. A squid is placed on the hook and lowered 20-30 m. The fishing line is tied to the boat with a restraining line to keep the hook at the desired depth. The restraining line is fairly heavy, about 100-lb (45 kg) breaking strength, because it is intended to set the hook when the fish strikes. Three well separated hooks are fished: one at the bow, one amidship, and one at the stern. Some boats fish a hook at each corner of the stern and one amidship. It seems that none of the boats fish more than three hooks at a time. While waiting for the tuna to strike the fishermen continue to fish for squid.

When a tuna strikes it is allowed to run a short while until the outgoing line is slow enough to grab. It is then pulled by hand to the boat. At this point the fishermen differ in their technique; some stun the fish and then gaff the fish; others gaff the fish and then stun the fish after it is on board. Fish are stunned with a blow on the head with a baseball bat or a wooden mallet.

When there is a strike at least one of the other two lines is removed from the water as soon as possible. The reason given for this action is that it reduces the possibility of the lines tangling. Tuna strikes tend to come in clusters and while it is possible to keep two lines with struggling fish from tangling it is almost impossible to keep three lines from tangling. The fishermen claim that tuna schools move away when the lines get tangled.

The fish are stored in iceboxes with a mixture of ice and seawater. Often the catch exceeds the icebox capacity. Excess fish are left on deck and covered with canvas or burlap. Seawater is poured on the covered fish periodically. Departure from the fishing ground is around 5 a.m. so that the fish can be delivered in time for the 7 a.m. auction.

GEAR

Two sets of gear are used. One set is for catching squid and the other for catching tuna. There is much individual variation in the choice of materials and design of the gear. The following description is of gear that seems to be in use by most.

Jigs and gaffs are used to catch squid. A typical jig (Fig. 2) has a shank 25 cm long and 8 prongs each of which is 5 cm long. Variation in the jigs occur in the number of prongs, which maybe 6-10, and in the linear dimensions, which vary about 10%. The head of the gaff (Fig. 3) is similar to the jig's with slightly longer prongs (7 cm).

Fig. 2

Fig. 3

The handle is a straight piece of bamboo a meter long and 2 cm in diameter at the larger end.

ig. 4 The tuna fishing gear (Fig. 4) consists of a hook, a leader,
 ig. 5 a lead weight, and a line. The hook (Fig. 5) is of a Japanese design
 footnote 1 (Tonkichi BKM #54)^{1/}. The leader is 7-strand stainless, 500-lb (227-kg)
 test, wire. The leader length preferred by most is about 1 m but
 leaders 0.6-1.8 m are used. The weight (Fig. 5) is a lead tube of 8-14
 oz (227-397 g). The tube is bent at the middle about 30° to keep it
 from rolling around on the boat. A stainless steel rod is placed
 through the tube and its ends are fashioned into eyes to facilitate
 the attachment of line and leader. The favorite material for the line
 is polypropylene rope either 3/8 in. (0.95 cm) or 5/16 in. (0.79 cm)
 in diameter. Lengths of the line range from 110 to 130 m. The fishing
 gear is coiled and kept in a square wooden box for easy handling.

Other equipment used by all boats are a parachute, lights, and a baseball bat. The parachute is 7.2 m in diameter and equipment surplus by the military. The lights, used for attracting squid, are of two types: above surface and underwater. Above surface lights are 25-W incandescent bulbs with polished metal reflectors. Usually two of these are used. The underwater light, usually one, is a 50-W incandescent bulb that has been waterproofed and weighted. Brighter bulbs are sometimes used for moonlit nights. The baseball bat is used for stunning fish.

^{1/} Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

A wide assortment of boats is used in this fishery. These range from 20-ft. (6-m) fiberglass skiffs to a 60-ft (18 m) boat that fishes longlines during the off season.

THE CATCH

The fishery catches bigeye tuna, Thunnus obesus, and yellowfin tuna, T. albacares, primarily. Albacore, T. alalunga, is a third tuna species that is commonly caught. The contribution of these species to the catch in weight and in value for the years 1973, 1974, and 1975 are listed in Table 1. The catch has increased from 89.1 metric tons to 154.6 metric tons during these years. The dollar value of the catch has increased at a slightly faster rate, from 141.1-327.5 thousand dollars.

Although the total tuna catch exhibited a continuous growth for the 3 years, the catches of the individual species fluctuated tremendously between years. In 1974 the bigeye tuna catch was almost twice as much as the other 2 years; in 1975 the yellowfin tuna catch was more than thrice the amount of the previous 2 years; and the albacore catch in 1975 increased by fiftyfold.

PROBLEMS

Some of the fishermen were asked what they thought was the biggest problem in the fishery. They unanimously expressed the need for a larger market. They felt that they would receive a better price for their catch with a larger market. (The average price for all tunas in 1975 was \$2.13 per kg.)

A problem that was observed to be common was an unsatisfactory flesh condition in which the normally deep red, translucent muscle tissue appears pink and opaque. In the trade this condition is called "burn." Scientists from the National Marine Fisheries Service have recently concluded that this condition is caused by inadequate chilling of the catch. Fish with "burn" sell for a fifth to a third of the normal price depending on the degree of burn.

DISCUSSION

The wide fluctuations in the catch of individual species portends an instability of the fishery. So far, however, a decrease in one species has been compensated for by an increase in another. Perhaps it is a natural state that a correlation exists among the availability of these species. Continued observation of this fishery is recommended to see if this is so.

The constant location of the fishery suggests that some environmental feature or a set of environmental features exist which concentrates the fish. It would be interesting, and possibly profitable, to study the oceanographic characteristics of the area of the fishery and to look for other areas with similar characteristics.

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Table 1.--Weight and value of tuna catch of night handline fishery.

	Weight metric tons			Value US\$ (thousands)		
	1973	1974	1975	1973	1974	1975
Bigeye	65.4	120.2	63.1	102.6	249.8	149.5
Yellowfin	23.3	22.9	75.5	38.0	38.4	157.0
Albacore	0.4	0.2	16.1	0.5	0.2	21.0
All tunas	89.1	143.2	154.6	141.1	288.2	327.5

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2. Drawing of hook for catching squid.
3. Photograph of a squid gaff.
4. Photograph of handline gear for fishing tuna.
5. Close-up of weight, leader, and hook.

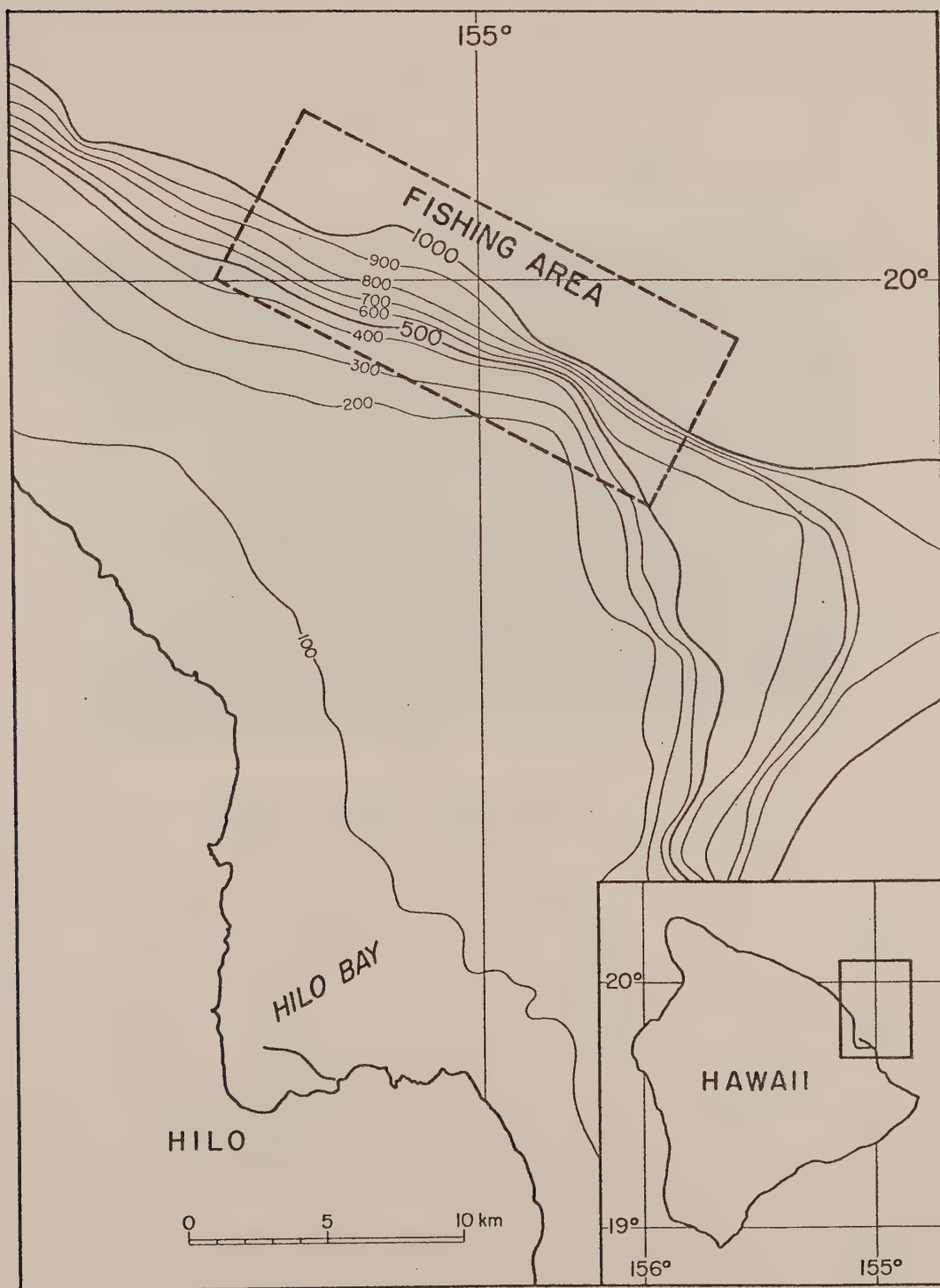


Figure 1.--Location of night handline fishery for tunas.



Figure 2.--Drawing of hook for catching squid.

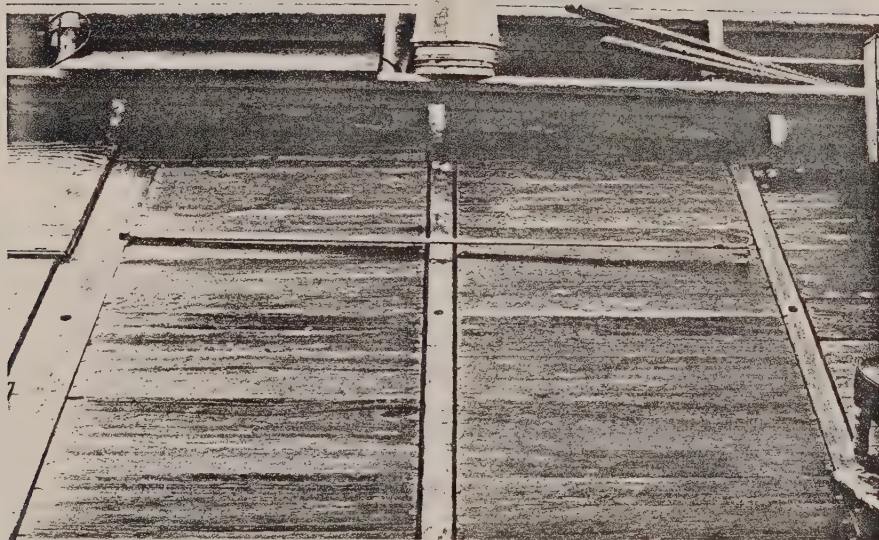


Figure 3.--Photograph of a squid gaff.

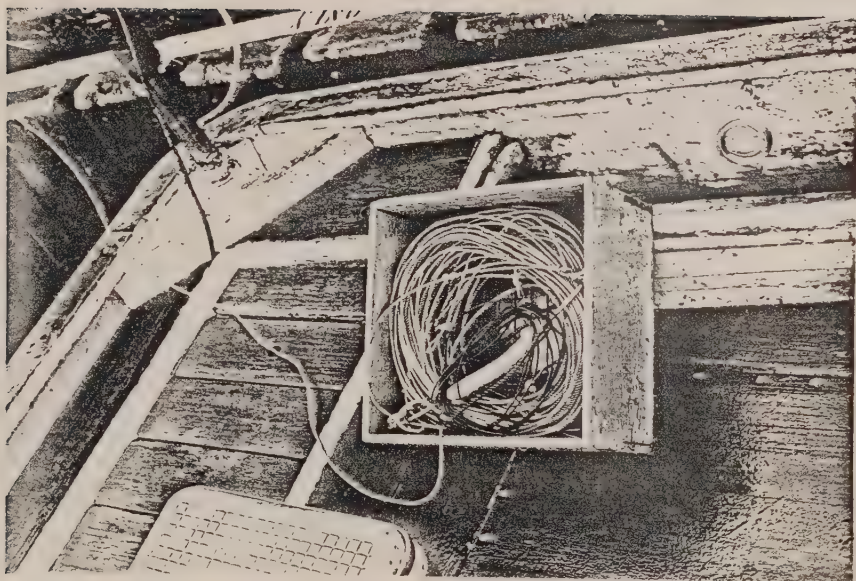


Figure 4.--Photograph of handline gear for fishing tuna.

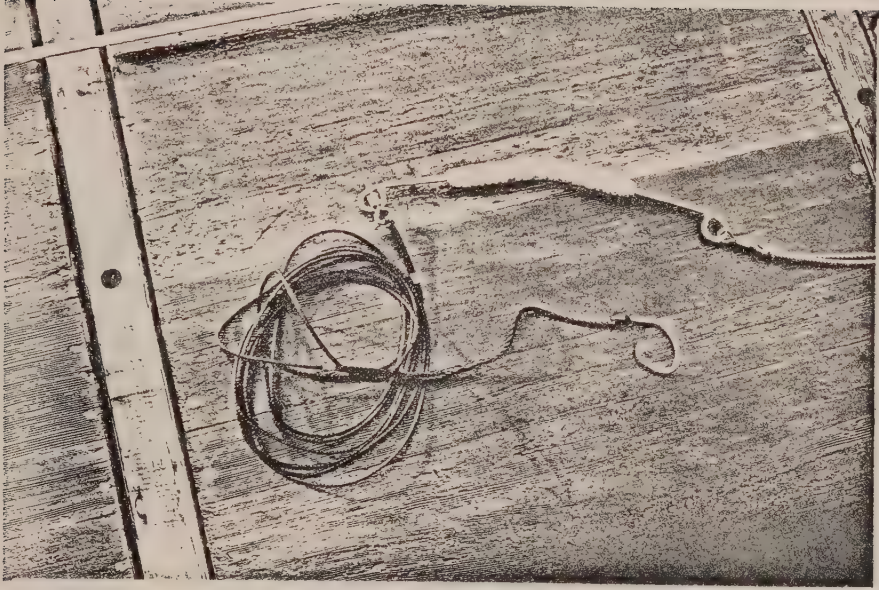


Figure 5.--Close-up of weight, leader, and hook.

THE COMMERCIAL MARINE FISH LANDINGS OF HAWAII, 1961-75

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THE COMMERCIAL MARINE FISH LANDINGS OF HAWAII, 1961-75

The fishery resources outside the immediate vicinity of many of the central and western Pacific islands have not been fished extensively. For these areas, there is a need to obtain estimates of the types of resources available and extent of these resources in order to provide for orderly development and management. The size and value of the fishery resources will undoubtedly contribute materially to the decision as to how these resources will be utilized; e.g., to meet domestic protein needs or exported for foreign exchange.

While definitive stock assessments of tropical fishery resources are needed, a first approximation of the type and size of the fishery resources in various island areas can be obtained by reviewing ongoing fisheries operating in areas with similar ecological habitats. The data from the existing Hawaiian Islands fisheries should provide considerable insight to the type and size of fishery resources one could expect from other island areas.

The following is a brief summary of the commercial fisheries of the Hawaiian Islands with special emphasis on the catch statistics from 1961 through 1975.

Fishery resources

The marine fauna of the Hawaiian Islands is typically of Indo-Pacific origin. Although the species complex is not as rich as in other areas of the Pacific, especially the western Pacific, it has been reported that there are about 682 species of fish in the Hawaiian Islands; however, fewer than 50 species contribute materially to the commercial fish landings.

The Hawaiian Archipelago consists of a series of volcanic islands, atolls, and banks ranging from Hawaii located to the southeast at 19°N latitude, 155°W longitude, to the Kure Island located at 28° 30'N latitude, 178°30'W longitude. The chain can be separated into two basic units; one the lower eight main islands which are mostly inhabited and of recent volcanic origin, and the northwestern Hawaiian Islands which are geologically older, uninhabited except for Midway Islands and French Frigate Shoals and which consist of extensive banks and atolls.

While some exploratory fishing has been carried out in the Northwestern Hawaiian Islands, the bulk of the commercial fishing effort has been concentrated around the main islands in the lower part of the Hawaiian chain.

Fishing played an important and active role in the lives of the ancient Hawaiians. A survey of the commercial fisheries of the Hawaiian Islands

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by John N. Cobb in 1901 indicated the total landings of fishery products in 1900 to be around 7,381,572 pounds. Although new resources are still being uncovered, e.g., deep-water shrimps (Struhsaker and Aasted, 1974), the fishery resources around the main Hawaiian Islands have been actively fished for decades. The pole and line fishery for skipjack was started in the early 1900's (Yamashita, 1958). Detailed data on the commercial catch have been recorded since the mid-1940's. Unfortunately, the catch and effort data from the recreational fishing sector are not presently being collected. Since recreational fishing effort is increasing dramatically, the total catch of this sector will undoubtedly become an important portion of the total catch. The total landings for Hawaii ranged from 4,400 metric tons in 1975 to a high of 8,900 metric tons landed in 1965. As shown in Figure 1, the bulk of the catch is made up of skipjack tuna. The fluctuations noted in the annual landings are dictated by the performance of the skipjack fishery. The ex-vessel value of the catch ranged from \$3.5 million in 1975 to \$5.2 million in 1965. Except for the recent increasing trend noted in 1975 the catch of other species has remained relatively constant during the 1961-75 period, ranging between 1,500 and 2,000 metric tons. The species listed in the "Others" category are taken by a variety of fishing methods and gear including handline, gillnet, traps, bag nets, longline, and surface trolling.

Figure 2 shows the fish landings from longline, deep handline, shallow handline, trolling, and "Others."

The Hawaiian longline fishery which at one time contributed significantly to the total commercial fish landings in Hawaii showed a marked decline in landings during the 1961-75 period. The decline from 959 metric tons to 334 metric tons in 1975 probably reflects a complex of reduced fishing effort along with lower catch rates. The landings of the deep-handline fishery, which includes the pink and red snappers, groupers, and other deep demersal fish species, declined in recent years and ranged between 175 and 200 metric tons. The catch shows an increase in 1975. There are indications that this fishery may increase in the coming years with the expansion of the fishery into the Northwestern Hawaiian Islands. Recent surveys by the National Marine Fisheries Service in the Northwestern Hawaiian Islands gave evidence of the presence of commercial quantities of deep-handline fishery resources, as well as of lobsters (Uchida and Hida, MS). The catches of the shallow-handline fishery, which generally takes place outside of the fringing reefs, include mackerels, goatfishes, squirrelfish, and jacks. The catch of this fishery approximated that of the deep-handline fishery and ranged in the neighborhood of 150 metric tons. As noted in Figure 2 the catches for both the deep-handline and shallow-handline fisheries have not changed materially during the 1961-75 period. The catches made by the troll fishery include fish caught by recreational boats and sold on the commercial markets. These include billfishes, tunas, mahimahi, and wahoo. The recent increases are probably attributable to the increased catches of yellowfin tuna by the recreational

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boats. In recent years recreational fishermen have learned that trolling in the vicinity of dolphins often results in catches of yellowfin tuna. A detailed breakout of the principal species caught by the deep-handline fishery is shown in Figure 3. The three most important species taken in this fishery are the opakapaka (Pristipomoides microlepis), onaga (Etelis carbunculus), and ehū (Etelis marshi). The landings of these three species all showed some fluctuations during the 1961-75 period. The details of the shallow-handline fishery are shown in Figure 4. As indicated the opelu and akule catches from this fishery were roughly the same, averaging roughly 50-60 metric tons. It should be noted here, however, that the total akule landings are considerably higher than the opelu landings since the bulk of the akule catch is currently made with bag nets.

The average price per kilogram of the three principal species caught by the handline is shown in Figure 5. From around 1967, there was a general increase in prices with very marked increases for the opakapaka and hapu'upu'u. The ex-vessel price of opakapaka increased from \$1.04 per kilogram in 1961 to \$2.38 in 1975. Next in importance was the hapu'upu'u (Epinephelus quernus) which increased from \$1.15 per kilogram in 1961 to \$2.35 in 1975. The akule (Trachurops crumenophthalmus) was the only species which showed a decrease in price during the 1961-75 period. During the 1961-75 period the akule price reached a high in 1963 of \$1.64 per kilogram. This declined to a low of \$0.79 per kilogram in 1968 and since then has increased to a high of \$1.26 per kilogram in 1975. The decrease in akule prices from 1964 has been attributed to a market increase in landings for this species. As indicated earlier the akule catches from the bag nets increased substantially during the 1960's.

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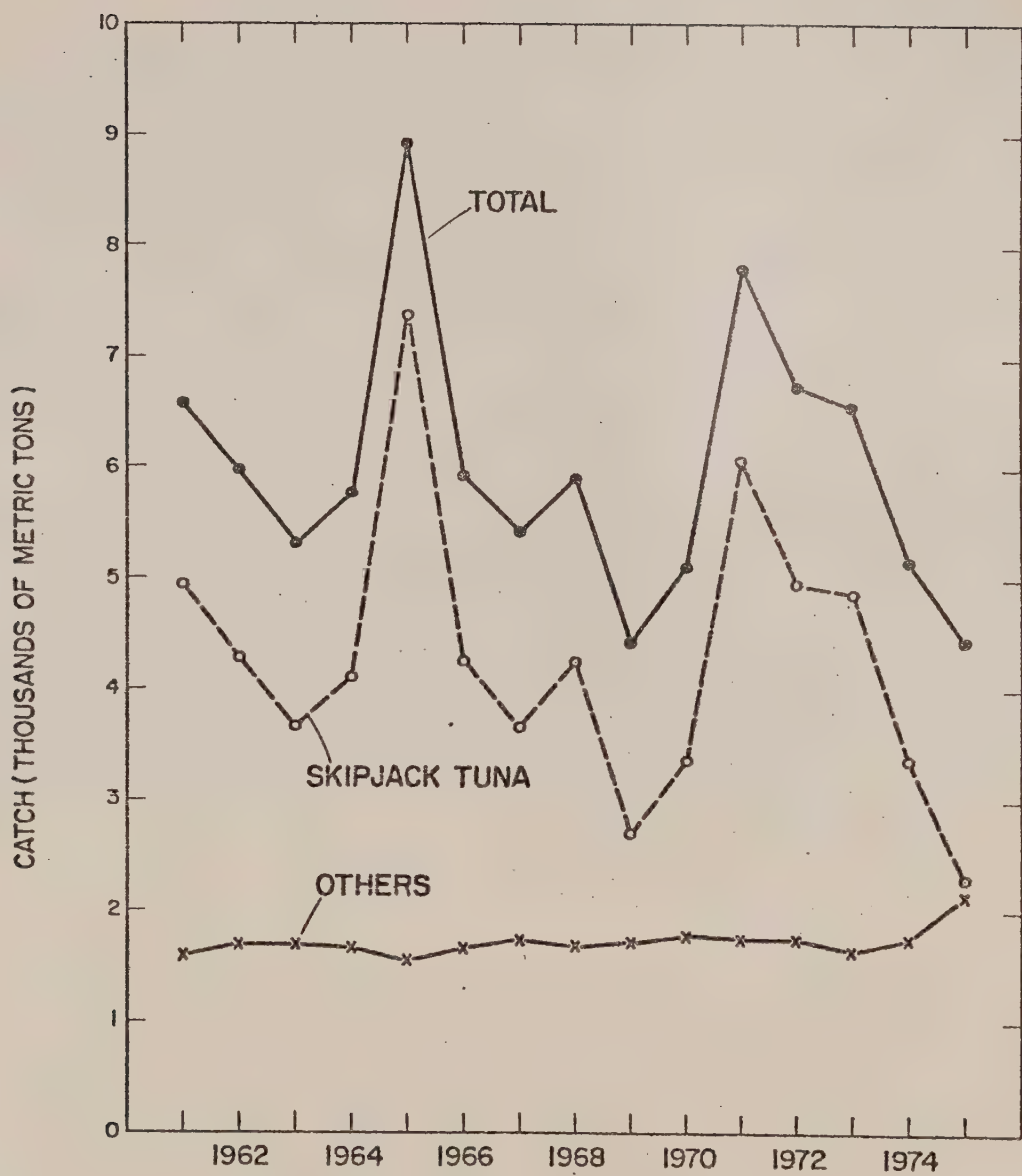


Figure 1.--Hawaii fish landings, 1961-75.

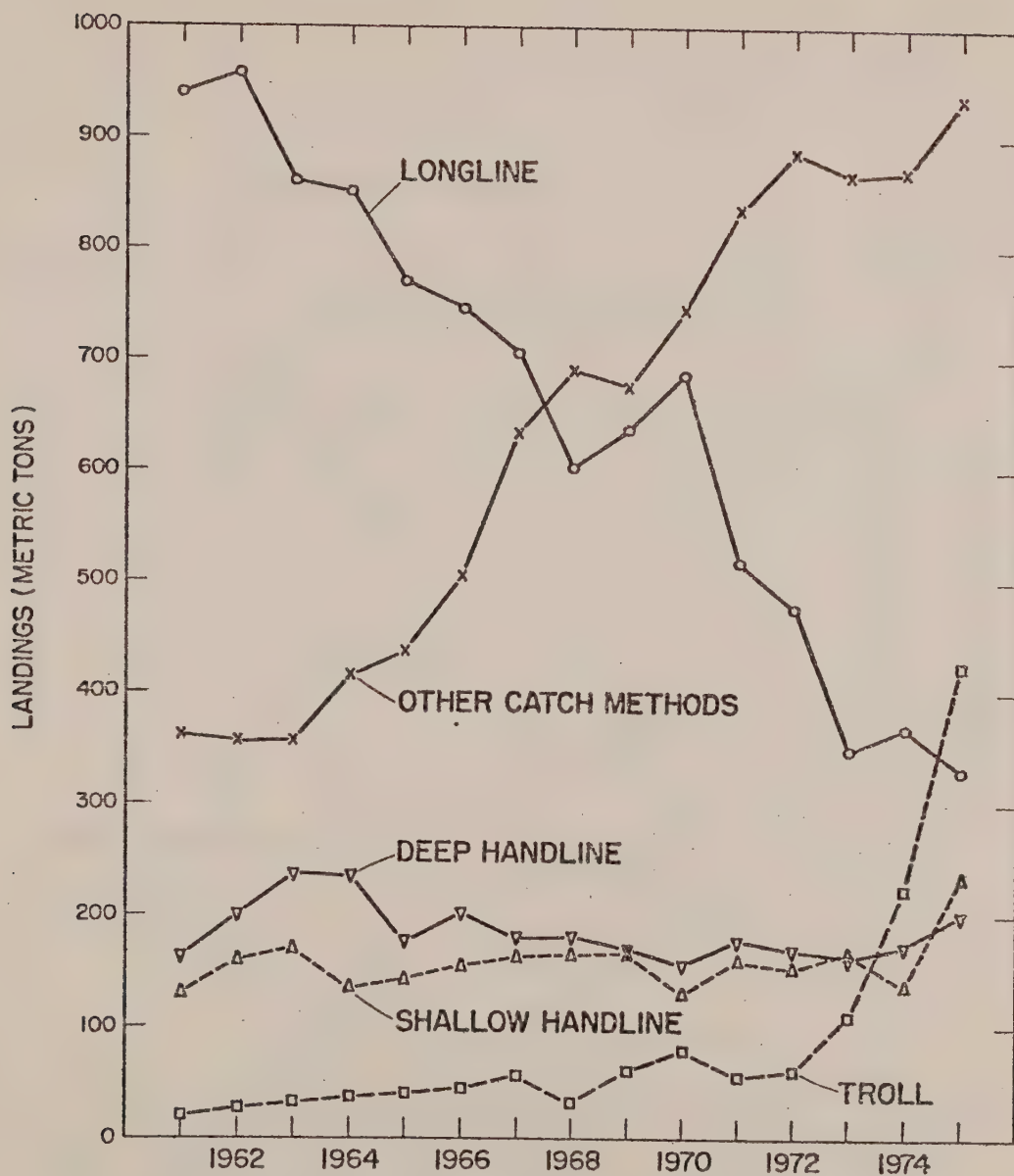


Figure 2.--Hawaii fish catch by gear.

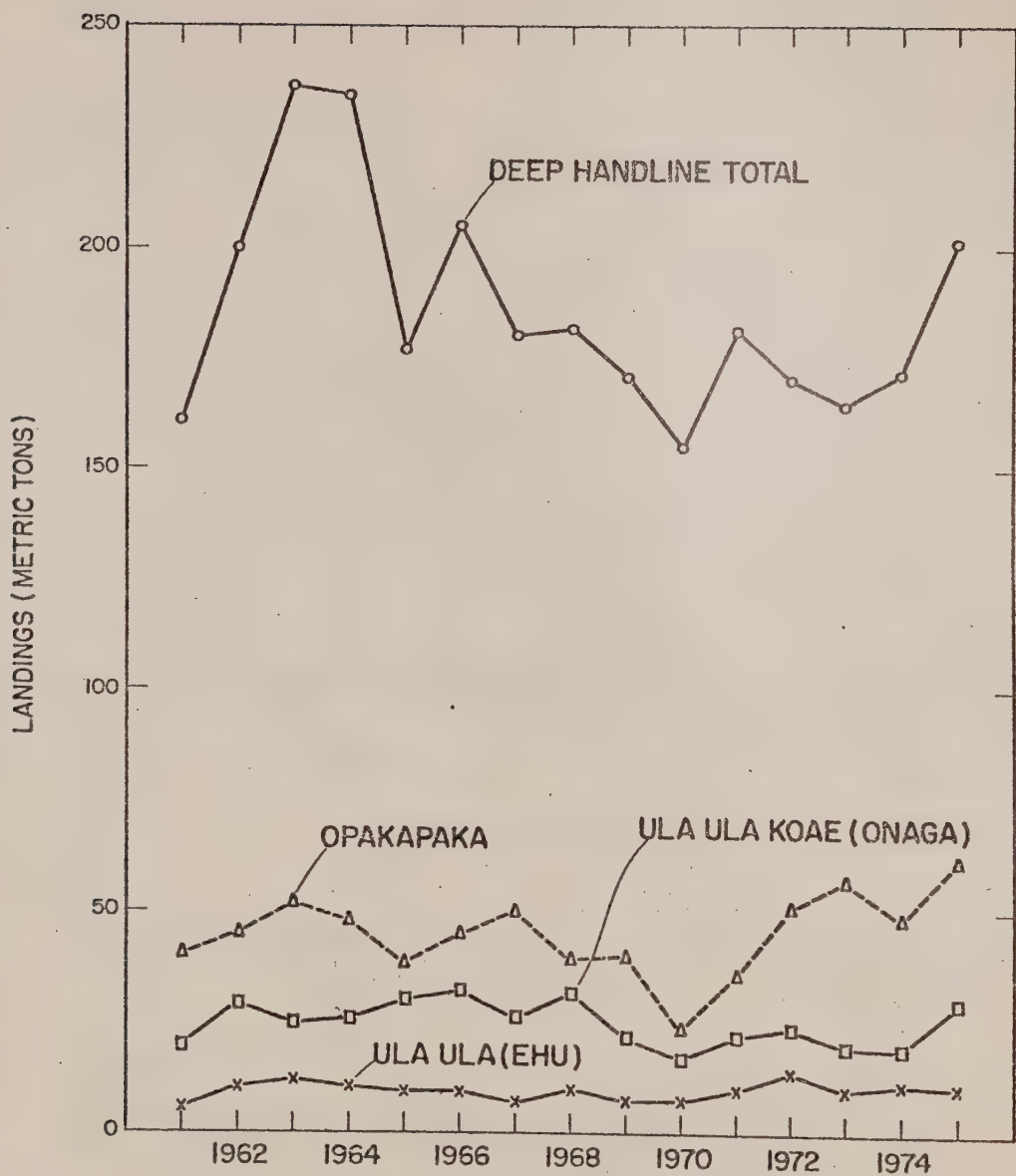


Figure 3.--Catch of the Hawaiian deep handline fishery, 1961-75.

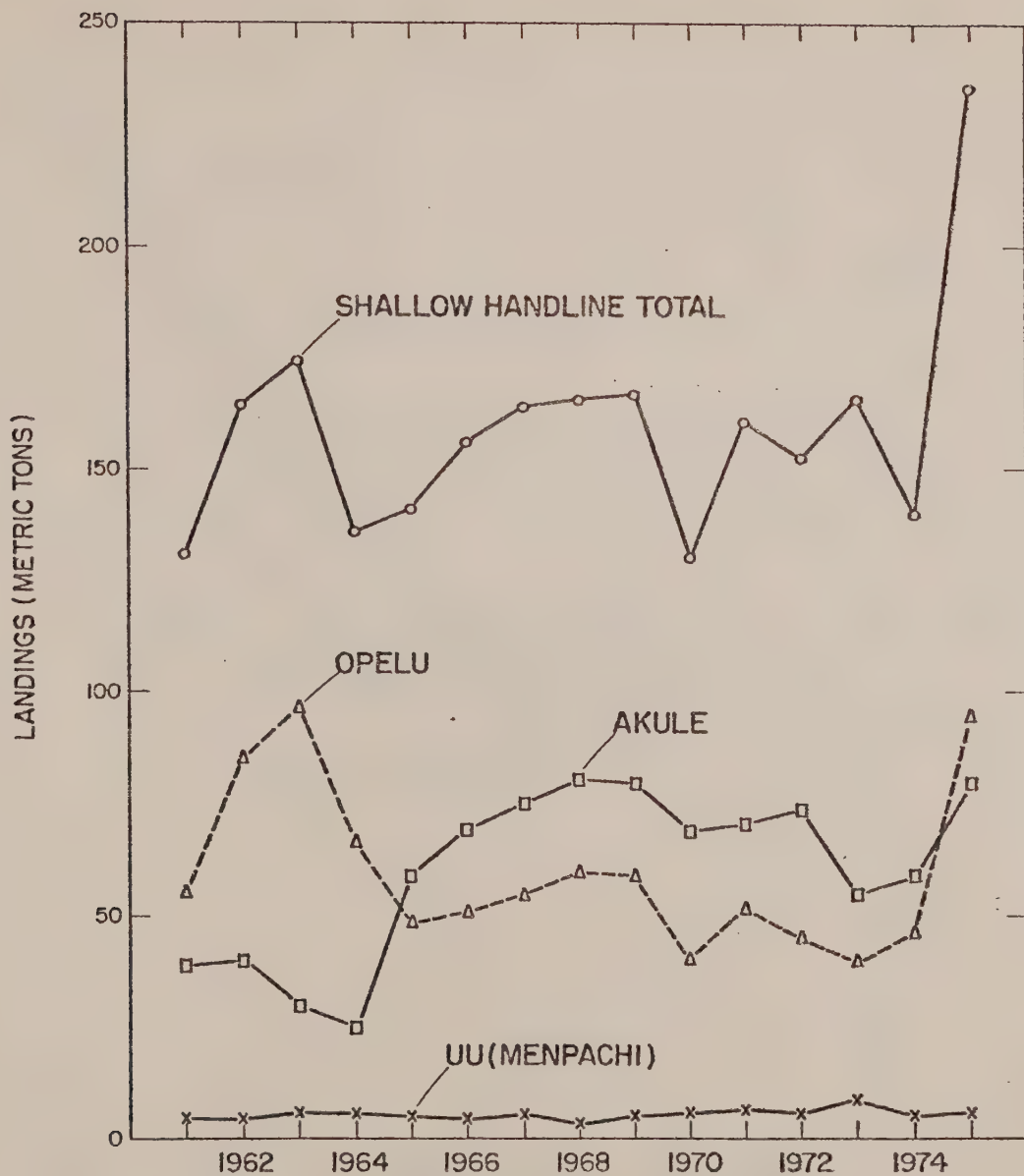


Figure 4.--Catch of Hawaiian shallow handline fishery, 1961-65.

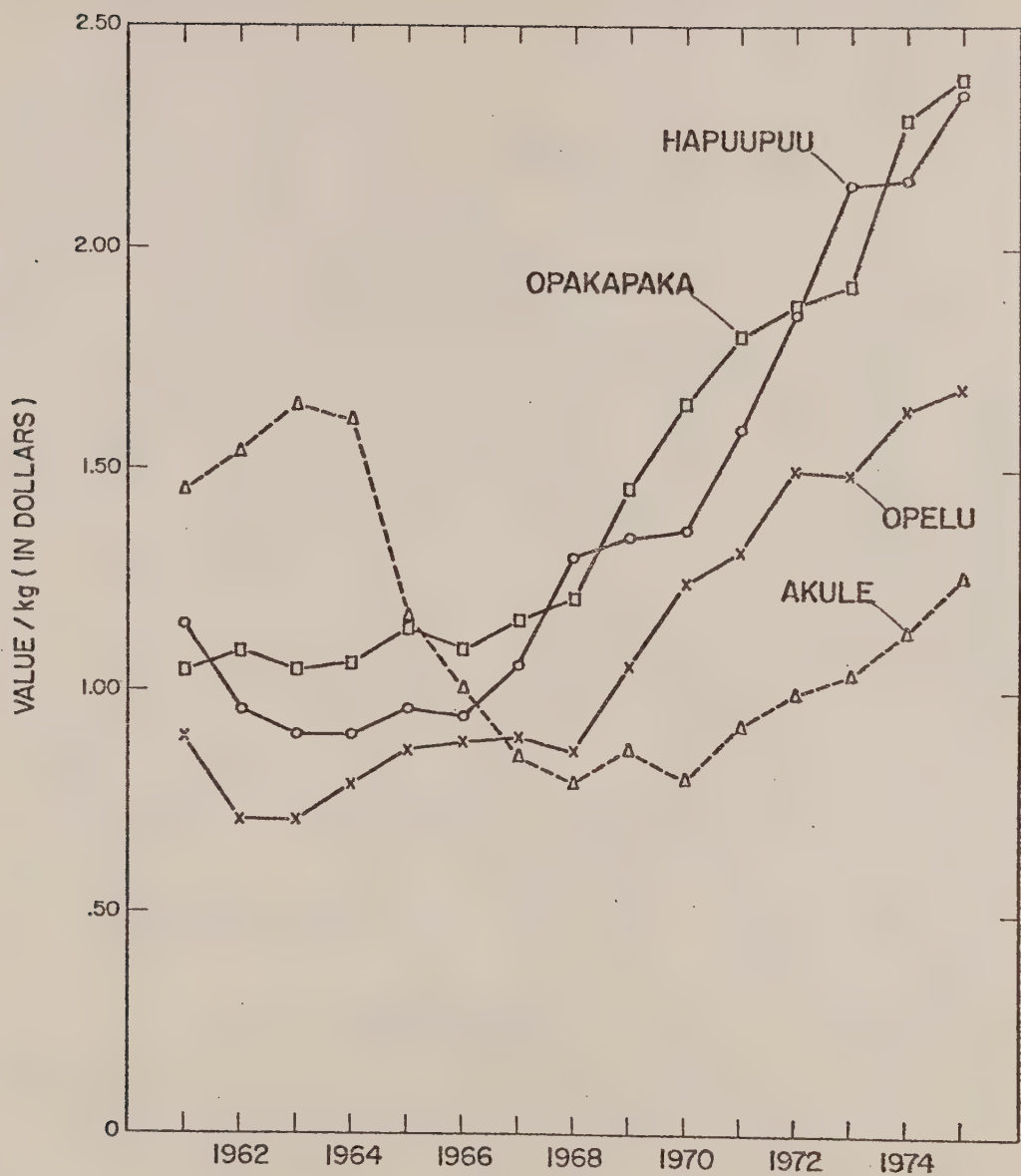


Figure 5.--Ex-vessel price of four principal species caught with handline gear.

A SUMMARY OF ENVIRONMENTAL AND FISHING INFORMATION
OF THE NORTHWESTERN HAWAIIAN ISLANDS

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This report does not constitute a publication and is for information only. All data herein are to be considered provisional.

INTRODUCTION

The Northwestern Hawaiian Islands (NWHI), often called the "Leeward chain" and which has been, with the exception of Midway, a wildlife sanctuary since 1909, stretches for over 1,800 km (1,000 mi.)¹ westward beyond the island of Niihau, one of the islands in the major Hawaiian group (Figure 1a). The tiny islands and atolls composing this "Leeward" chain have been worn down to vestiges of their former estate and support only a limited assortment of animals and plants (Carlquist 1970). The flora, for example, is similar to that of a tropical beach with virtually all the plants near the shore with a few exceptions. Crowding these islands is a rich assortment of marine and shore birds.

There is a great urgency to know a great deal more about the marine resources of these NWHI. The State of Hawaii, pressed with growing demands for an assessment and rational utilization of its marine resources, recognizes the vital importance of the sea to its economic growth and has fostered a program of harvesting the marine resources of the waters surrounding the entire Hawaiian chain (State of Hawaii 1969, 1974). Furthermore, the Fishery Conservation and Management Act of 1976 will extend U.S. jurisdiction over the fishery resources to within 200 nautical miles from our nation's coastline. Some foreign nations already restrict U.S. fishermen from the

¹Throughout this report, distances are given in kilometers followed by their equivalent in statute miles over land and nautical miles over the ocean.

traditional fishing grounds off their coasts, but as others follow their example, there will be increased pressure from the fishing industry to find new fishing grounds.

There are also conflicting demands for utilization of the NWHI's resources. The U.S. Department of the Interior's Fish and Wildlife Service (FWS) has maintained the wildlife refuge for the protection and benefit of its inhabitants--sea birds, seals, and turtles.

The National Marine Fisheries Service (NMFS) in Honolulu has proposed a cooperative study to survey and assess the marine resources of the NWHI. An intensive 5-year investigation, with the Hawaii Division of Fish and Game, FWS, and the University of Hawaii Institute of Marine Biology and Sea Grant participating, will include assessment of the terrestrial, nearshore, slope, and pelagic resources of the NWHI and their interrelationships.

The purpose of this report is to review and summarize all available information, published or unpublished, on the environment and marine resources of the NWHI.

DESCRIPTION OF THE ISLANDS

The NWHI is part of the Hawaiian chain which rises above an elongated submarine ridge that stretches roughly 3,200 km (1,700 mi.) in a southeast-northwest direction (Freeman 1951). Constructed of volcanic material that was erupted from a zone of fissures on the

ocean floor, the Hawaiian chain consists not only of visible islands but also of several submarine peaks and numerous banks.

Beginning at Kure atoll, it is possible to trace the history of the formation of the Hawaiian Islands through a sequence of eruptions which has continued over the years from west to east (Carlquist 1970). Even within each island, the oldest part is to the west and the newest to the east. Because of this clear sequence of formation, it is hypothesized that the atolls of the NWHI are vestiges of once high volcanoes that have been worn down through the ages into low, sandy atolls. Many of the atolls and islands are surrounded by banks, some of them shallow (Figure 1).

Based on the nature of the islands and the stage of erosion, the Hawaiian chain may be divided into the southeastern portion, which is composed of the eight high volcanic islands or the present major islands, the middle portion including Kaula Island near Niihau, Nihoa, Necker, French Frigate Shoals, La Perouse Pinnacle, and Gardner Pinnacles, and the northwestern part consisting of low atolls, sandy islets, reefs and shoals including Laysan, Lisianski, Pearl and Hermes Reef, Midway and Kure (Carlquist 1970; McDonald and Abbott 1970). The area and altitude of the islands and atolls in the Hawaiian chain are given in Table 1.

KAULA ISLAND

Kaula Island, a crescent-shaped tuff cone, lies 43 km (23 mi.) southwest of Niihau and actually belongs with Kauai and Niihau rather

ig. 2

than with the rest of the Leeward chain (McDonald and Abbott 1970). Resting on a broad base that is a big submerged volcano, the island lies near the southeastern edge of a shoal which is 13 km (8 mi.) long in a west-northwesterly direction, 7 km (4.5 mi) wide, and roughly 61 m (200 ft) below sea level (Figure 2). McDonald and Abbott concluded that this flat platform must have been cut across the top of the shield volcano by wave action. A projection rises to about 9 m (30 ft) below sea level near Kaula and is probably an erosional residual rather than another cone rising from the platform. Kaula rises about 168 m (550 ft) above sea level. Its position is given by Bryan (1942) as lat. $20^{\circ}39'N$ and long. $160^{\circ}31'W$.

NIHOA ISLAND

ig. 3

The first of the uninhabited islands to the northwest of the major Hawaiian group is Nihoa, which is located at lat. $23^{\circ}06'N$ and long. $161^{\circ}58'W$, roughly 315 km (170 mi.) west northwest of Kauai (McDonald and Abbott 1970). This small volcanic island, plainly visible from a great distance, is 1.4 km (0.85 mi.) long, averages about 457 m (1,500 ft) wide, and is the largest of the lava islands west of Niihau (Figure 3). The island has two peaks--Miller's Peak on the west and rising 273 m (895 ft) above sea level and Tanager Peak on the west rising 260 m (852 ft). A broad swale separates the peaks.

The island covers about 0.7 sq km (175 acres) (Carlquist 1970). The northern edge of Nihoa is an abrupt sea cliff, which

plunges directly from the crest of the island into the water (McDonald and Abbott 1970). On the southern side, the land slopes fairly gently to low bluffs near the coast where it is truncated by a sea cliff towering 15-30 m (50-100 ft) high with a wave-cut platform at the base and about 1.2-2.4 m (4-8 ft) above sea level. The east and west ends of the island are also inaccessible cliffs (Emory 1928).

All the lava flows on Nihoa dip southwestward. Emory (1928) reported that less than half of the area of Nihoa is comprised of gently sloping ground covered with several varieties of grass.

Extending northwestward from the island for about 29 km (18 mi.) is a platform about 37 to 76 m (120 to 250 ft) below sea level (McDonald and Abbott 1970). Apparently, the whole northwestern part of a volcanic island, perhaps 32 km (20 mi.) across at sea level, has been eroded by wave action. Another bank at the 30-46 m (100-150 ft) depth range lies 33 km (18 mi.) west southwest of Nihoa; it is about 27 km (17 mi) long and 19 km (12 mi.) wide.

Nihoa has a large population of nesting seabirds giving the island its former name of Moku Manu (Bird island) (Emory 1928; McDonald and Abbott 1970). Sheets of guano coat some of the cliffs. Also, on the southern side, some of the valleys are partly filled with a conglomerate in which a mixture of clay and guano predominate in the cement.

Remains of home sites and terraces used for cultivation are abundant evidence that the island was formerly occupied by people in the past (McDonald and Abbott 1970). How the inhabitants obtained

their water is still speculative. Archeological explorations have found several seeps on the islands, the principal one 82 m (270 ft) high; the water, however, is somewhat brackish and heavily tainted with guano.

NECKER ISLAND

Necker is a narrow bit of land less than 1,200 m (4,000 ft) long and about 150 m (500 ft) wide (McDonald and Abbott 1970). Lying 556 km (300 mi.) northwest of Niihau at lat. $23^{\circ}34'N$ and long. $164^{\circ}42'W$, the island covers 0.2 sq km (41 acres) with its highest point 84 m (276 ft) above sea level (Figure 4). Emory (1928) described the island as shaped like a fishhook with the shank lying in an east-west direction and the barb, the northwest cape, measuring about 183 m (600 ft) long and 61 m (200 ft) wide. At the east end is an islet about 61 m (200 ft) long and 23 m (75 ft) wide; it is generally awash (McDonald and Abbott 1970).

Necker lies on a shallow, roughly oval platform which measures 61 km (38 mi.) long in the northwest-southeast direction and about 32 km (20 mi.) wide (McDonald and Abbott 1970). The positions of the island and the former volcano center within this platform, which undoubtedly has been eroded over the years by wave action, indicate that the core was not a single shield volcano, but a group of shields similar to the present island of Hawaii. (Shield volcano is built up by successive outpourings of lava with little or no

fragmental material.) Necker itself is composed of vertical dikes and is an eroded remnant of one of the shield volcanoes.

Although presently uninhabited except by innumerable seabirds, Necker once had a sizable human population (McDonald and Abbott 1970). Remains of fishponds, ditches, agricultural terraces, and house and temple platforms attest to the occupation of the island by humans. Furthermore, it has been conjectured that many of the ruins and artifacts appear to have been left by an early group of people, who preceded the more recent Hawaiians.

As on Nihoa, the source of fresh water is a mystery (McDonald and Abbott 1970). The present supply appears to be about 38 liters (10 gal) per day of undrinkable, guano-tainted water.

FRENCH FRIGATE SHOALS

Located almost at the midpoint of the 3,200-km (1,700-mi.) long Hawaiian Archipelago (Figure 5), French Frigate Shoals is about 1,360 km (735 mi.) northwest of the eastern tip of the island of Hawaii and 1,445 km (780 mi.) southeast of Kure Atoll (Amerson 1971). There are 13 small named islands in the lagoon; 12 are low and sandy with sparse or no vegetation whereas the remaining island is a volcanic rock.

Officially located at lat. $23^{\circ}45'N$ and long. $166^{\circ}10'W$, the atoll consists of a crescent-shaped reef on a 36-m (20-fathom deep oval platform (Amerson 1971). Palmer (1927) reported that this platform, at a depth of 55 m (30 fathoms), covers about 648 sq km (250 sq mi.).

The atoll, with the long axis stretching 35 km (22 mi.) in a northwest-southeast direction, is actually a double crescentic reef (Amerson 1971). The 363-sq km (140-sq mi.) lagoon is 13 km (8 mi.) wide at its midpoint, whereas the broken inner arc of the reef is 33 km (21 mi.) long and the almost continuous outer arc is 57 km (36 mi.) long. The crescent tips, pointing westward, are about 28 km (17 mi.) apart with La Perouse Pinnacle lying on an imaginary line between these two tips about 11 km (6 mi.) southeast of the northern tip and 17 km (9 mi.) northwest of the southern tip.

The 12 sand islands of French Frigate Shoals cover 0.4 sq km (111.3 acres) of which 0.1 sq km (33.3 acres) are covered with vegetation (Amerson 1971). Two exposed volcanic rocks exist near the center of the oval platform. Islands with well-established vegetation include East, Tern, Trig, and Whale Islands. Skate and Little Gin Islands, although quite large, are only sparsely vegetated. Two other large islands--Gin and Disappearing--are without vegetation and La Perouse Pinnacle, in spite of its size and height, supports no vegetation. The rest--Bare, Mullet, Near, Round, and Shark Islands--are sandbars that shift continuously. Three other nameless sandy islets are submerged during periods of high tide.

Tern Island, the largest island in the atoll and located near the northwest tip of the crescent, is a man-made island about 945 m (3,100 ft) long (Amerson 1971). A runway 76-m (250-ft) wide extends the length of the island. Tern island is presently used as a U.S. Coast Guard loran station.

La Perouse Pinnacle (Figure 5), located at lat. $23^{\circ}45'N$ and long. $166^{\circ}15'W$, is 11 km (6 mi.) south-southeast of Tern and 6 km (3 mi.) west-southwest of East Island (Amerson 1971). Shaped in the form of a saddle, the main pinnacle at the northwestern end rises 37 m (122 ft) above sea level whereas at the southeastern end it is nearly as high at 36 m (120 ft). The main rock is roughly 222 m (730 ft) from northwest to southeast and 50 m (165 ft) at its widest point. A second rock, lying 119 m (390 ft) northwest of the main pinnacle, rises about 3 m (9 ft) above sea level and about 61 m (200 ft) long, northwest to southeast, and 20 m (65 ft) wide.

GARDNER PINNACLES

Gardner Pinnacles, which consist of two small volcanic rocks in the middle of the NWHI, are located at lat. $25^{\circ}00'N$ and long. $167^{\circ}55'W$ (Figure 6) (Clapp 1972). Being the westernmost volcanic island in Hawaiian waters, Gardner Pinnacles stand on the northeastern part of a bank which is 32 km (20 mi.) wide and 80 km (50 mi.) long with depths ranging between 16 and 73 m (9 and 40 fathoms).

The northwestern peak of Gardner Pinnacles, the smaller of the two islands, rises about 30 m (100 ft) above sea level and is about 76 m (250 ft) long and 30 m (100 ft) wide (Clapp 1972). About 46 m (150 ft) to the southeast is the larger peak, which is about 213 m (700 ft) long and 152 m (500 ft) wide (Palmer 1927; Bryan 1939). Clapp (1972) reported that the larger peak formerly rose to 52 m

(170 ft), but its height was reduced by blasting in 1961 to provide sites for astronomic stations. The two islets have an overall area of about 0.01 sq km (3 acres) (Freeman 1951). From a distance, Gardner Pinnacles have a snow-capped appearance because of the liberal coating of guano (Clapp 1972).

LAYSAN ISLAND

ig. 7

Laysan Island, roughly rectangular in shape with the long axis slightly east of north, is the largest of the NWHI and is located at lat. 25°42'N and long. 177°44'W (Figure 7) (Ely and Clapp 1973). Situated 213 km (115 mi.) east of Lisianski, 374 km (202 mi.) northwest of Gardner Pinnacles, and 1,314 km (709 mi.) northwest of Honolulu, Laysan is 2,858 m (9,375 ft) long and just over 1,700 m (1 mi.) wide. Warner² estimated a total area of slightly under 4 sq km (913 acres).

The island, probably the flattened top of a once massive volcanic peak, is capped by large sand accumulations and has a large saltwater lagoon occupying about one-fifth of the island's central interior (Ely and Clapp 1973). Relatively shallow water surrounds the island for some distance offshore; the bottom drops off precipitously to an average depth of 3,293 m (1,800 fathoms). Warner (1963) estimated that the 180-m (100-fathom) contour around Laysan encloses an area of

²Warner, R. E. Completion report--Midway and Laysan Islands bird studies. Manuscript in preparation. Hawaii Division of Fish and Game, State of Hawaii, 11 p.

about 544 sq km (210 sq mi.). The maximum crest elevation is just over 12 m (40 ft) and occurs in the sand dune area at the north end of the island.

Presently, Laysan is well vegetated except for coastal dunes that appear to be well stabilized (Ely and Clapp 1973). The original flora, the most varied in the NWHI, was destroyed by man and introduced rabbits. By 1923, the island was in near desert condition and several species became extinct. The abandonment of the island by man permitted the vegetation to recover, nearly restoring the original conditions that existed in the past.

LISIANSKI ISLAND

Lisianski is a low sand and coral island which covers approximately 1.8 sq km (450 acres) and is situated at lat. 26°02'N and long. 174°00'W (Figure 8) (Freeman 1951; [U.S.] Office of Geography 1956). At a location about 1,677 km (905 mi.) northwest of Honolulu (Bryan 1942), Lisianski is at the northern end of a large reef bank which is about 168 sq km (65 sq mi.) in total area (Clapp and Wirtz 1975). The island, which has a circumference roughly 5 km (3.2 mi.), resembles a parallelogram with the north-south axis about 1,829 m (2,000 yd) long and the east-west axis 1,006 m (1,100 yd) wide.

The island is ringed by mostly sandy and sand-coral beaches with the exception of the eastern side which is dominated by an exposed ledge of reef rock and small tidal pools (Clapp and Wirtz 1975). Near the middle of the western beach is a small cove which is designated

a small-boat landing on the hydrographic charts. At the north end of the cove is a group of Casuarina trees. A rim of Scaevola growth covers the island's entire perimeter with the densest growth along the north point and southward along the east beach and across the south end. Lush growth of bunchgrass, Eragrostis, attaining heights of up to 1 m (3 ft) or more, covers the island's interior.

PEARL AND HERMES REEF

Fig. 9

One hundred sixty kilometers (87 mi.) east southeast of Midway Atoll and about 1,931 km (1,042 mi.) northwest of Honolulu is Pearl and Hermes Reef, a low coral atoll near the northwestern end of the Hawaiian Archipelago (Figure 9) (Amerson, Clapp, and Wirtz 1974). Given an official location of lat. 27°55'N and long. 175°45'W, this atoll has been known as Pearl and Hermes Reef since two ships bearing these names were wrecked there in 1822.

The fringing reef of this atoll has a circumference of 69 km (43 mi.) and is open to the west (Thorp 1936). The long axis of the elliptical enclosed area, oriented in a northeasterly direction, is 32 km (20 mi.) and the broadest point 18 km (12 mi.). Gross et al. (1969) estimated that the area within this reef covers 370 sq km (143 sq mi.). Nine islands within the reef cover 0.3 sq km (85 acres) (Amerson et al. 1974). Grass, North, Seal, and Southeast Islands have established vegetation; Little North Island, which has continued to emerge since it was first reported as a sandbar awash at high tide, has limited vegetation. Kittery Island is low and subject to

occasional inundation despite its size and relative permanency. The remaining three islands--Bird, Planetree, and Sand--are shifting sandbars. Historical and recent data examined by Amerson et al. (1974) suggest that considerable changes in the topography of Pearl and Hermes Reef have occurred in the past 100 years as a result of continuous shifting, splitting, and reforming of sandspits.

MIDWAY ISLANDS

Fig. 10

Lying about 2,101 km (1,134 mi.) west northwest of Honolulu at lat. 28°12'N and long. 177°23'W, Midway atoll is near the extreme western end of the Hawaiian Archipelago and consists of two islands (Figure 10). These islands are situated on the southeastern part of a lagoon, which is within a protective coral reef with a circumference of 24 km (15 mi.) and which is submerged in some places but about 1.2-1.5 m (4-5 ft) above water level in others. Of the two islands, Sand Island, on which the active runway is built, is larger. It measures 2.4 km (1.5 mi.) long and 1.6 km (1 mi.) wide (Bryan 1942). About 1.6 km (1 mi.) east of Sand Island is the smaller Eastern Island, which is triangular and measures about 2.0 km (1.3 mi.) long and 1.2 km (0.8 mi.) wide.

The entrance to the lagoon is on the south side between Sand and Eastern Islands (Tudor 1972). In 1905, Sand Island was converted into a submarine cable station and in 1936, it was designated a transpacific station for the China Clipper. According to Bryan (1942),

the single most outstanding feature with respect to the natural history of Midway is the change which Sand Island has undergone through the efforts of man. Because this island had no trees and scarcely any herbaceous plants to hold the shifting sand in place when the cable station was first established, a coarse grass, Ammophila arenaria, was imported from the wind-swept beaches near San Francisco. To provide windbreaks, ironwood trees, Casuarina equisetifolia, were planted in 1907 as well as numerous other ornamental trees, shrubs, and herbs. Soil was also brought in from Honolulu to encourage growth of useful plants. Midway was converted into a U.S. naval base in 1939 and is presently under administrative control of the Department of the Navy.

KURE ISLAND

g. 11 Claiming the distinction of being the northernmost coral atoll in the world and the westernmost land of the NWHI, Kure atoll, located at lat. 28°25'N and long. 178°10'W, is about 2,177 km (1,175 mi.) northwest of Honolulu and 4,012 km (2,165 mi.) southeast of Tokyo (Figure 11) (Woodward 1972). The closest neighboring island to Kure is Midway, 91 km (49 mi.) to the southeast. Kure, situated atop a submerged volcano, is nearly circular; the outer reef almost completely encircles the lagoon except for passages to the southwest. The maximum diameter is about 9 km (6 mi.). Gross et al. (1969) estimated that the reef comprises an area of about 5 sq km (1,235 acres). The lagoon depth is about 14 m (46 ft).

The only permanent land in the atoll is crescent-shaped Green Island located near the fringing reef in the southeast part of the lagoon (Woodward 1972). Its long axis curves north to west 2 km (1.4 mi.) and the maximum width is 0.6 km (0.4 mi.). The ocean side of Green Island is devoid of sand dunes and the elevation here does not exceed 5 m (15 ft). Sandy beaches encircle the entire island. The lagoon side is dominated by a series of sand dunes which vary up to 8 m (25 ft) in height. The dunes decrease in elevation southwest along the beach, whereas eastward behind them is a low, relatively flat depression in the surface with elevations varying from 2 to 3 m (6 to 10 ft).

The dominant features of Kure atoll are the man-made 190-m (625 ft) loran tower and transmitter building, the 21-m (70-ft) high radar reflector, the 1,219-m (4,000-ft) runway, and the building complex near the center of the island (Woodward 1972). Covering much of the island except for man-made open areas and the natural central plain where only low herbaceous plants grow is a dense growth of Scaevola taccada.

CLIMATE

The climatological data from the NWHI are primarily from French Frigate Shoals, Midway Islands, and Kure Island where man-made installations and operational personnel are located. Climatic data collected from Midway Naval Station can be used to describe weather

conditions not only at the atoll but also the nearby atolls of Lisianski and Pearl and Hermes Reef (Amerson et al. 1974; Clapp and Wirtz 1975).

Along the Hawaiian chain, the marine influence upon the climate is very significant because of the extreme insularity (U.S. Weather Bureau 1961). The mountains, however, especially the massive ones on Hawaii and Maui, strongly modify this marine effect with the result that conditions are somewhat continental in some localities. In the NWHI, however, the low profile of the islands and atolls results in conditions that are almost wholly marine and tropical.

A prominent feature of the air circulation across the tropical Pacific is the general east to west flow of the trade winds (U.S. Weather Bureau 1961). In the central North Pacific, the trades blow from the northeast quadrant and represent an outflow of air from the Pacific anticyclone, a region of high pressure. This Pacific high and trade wind zone move north-south seasonally reaching their northernmost positions in May-September, at which time the trades prevail 80%-95% of the time. In October-April, the Hawaiian Archipelago is positioned to the north of the heart of the trades; as a result, the frequency of trades decreases to 50%-80%. In general, then, the Hawaiian climate is characterized by a two-season year.

AIR TEMPERATURE

Temperatures recorded at French Frigate Shoals show variations that are typical of a tropical marine environment (Amerson 1971).

Fig. 12 Figure 12 shows the mode of the mean monthly temperatures and the range of the maximum and minimum modes of temperature for French Frigate Shoals in December 1950-December 1962. The mean annual temperature was 24.2°C (75.5°F) and the mean annual range was 5.6°C (10°F). In December-April, the means varied between 21.7° and 23.3°C (71° and 74°F) whereas in May-November, they varied from 23.9° to 26.7°C (75° to 80°F). August-September were the warmest months; February-March the coolest. The extreme high and low in the 12-year period studied were 32.8° and 12.2°C (91° and 54°F), respectively, a difference of 20.6°C (37°F).

Temperatures at Midway showed a mean monthly range of 7.2°C (13°F), which is indicative of a marine environment (Mauck 1975).

Fig. 13 Figure 13 shows that the means varied from 18.9° to 20.6°C (66° to 69°F) in December-April and from 21.1° to 27.2°C (70° to 81°F) in May-November. The warmest months were July-September and the coolest January-February and April. The extreme high of 31.7°C (89°F) and low of 11.1°C (52°F) differed by 20.6°C (37°F). The monthly maximum, minimum, and mean temperatures at Midway in 1949-72 are given in

Table 2 Table 2.

Kure's climate is described as subtropical marine and is influenced primarily by two air masses and by the surrounding ocean where changes in sea-surface temperatures and salinities are relatively small (Woodward 1972). For example, Seckel (1962) has shown that in this area, sea-surface temperatures vary from 20.5°C (69°F) in February to 26.7°C (80°F) in August-September and salinities from 35.0‰ in November-February to 35.2‰ in April-August.

At Kure, Woodward (1972) observed yearly variation occurring in the average semimonthly temperatures but concluded that the pattern of temperature change throughout the year was the same. For example, the data showed that the average maximum varied 11.2°C (20°F) from 18.2° to 29.4°C (65° to 85°F) and the average minimum about 9.5°C (17°F) from 14.4° to 23.9°C (58° to 75°F). The extremes were 3.8°C and 37.2°C (39° and 99°F), a difference of 33.4°C (60°F) (Table 3).

In December-April, the semimonthly maximum averaged 21.1°C (70°F), but in May-June and November, the averages varied between 21.1° and 26.7°C (70° and 80°F). Averages of 26.7° to 32.2°C (80° to 90°F) occurred in June-October. The average semimonthly minimums varied between 15.6° and 18.3°C (60° and 65°F) in December-May and between 21.1° and 23.9°C (70° and 75°F) in November (Table 4).

The coldest months at Kure were January and February and the warmest July-September (Woodward 1972). The average temperature usually increased in May although the rise sometimes occurred in June. A decrease in average temperature was usually observed in September or October.

WIND DIRECTION AND VELOCITIES

French Frigate Shoals is influenced most of the year by the Pacific high with easterly trades predominating (Amerson 1971). In winter, the Aleutian low moves southward to the Kure-Midway-Pearl and Hermes area affecting the Pacific high slightly and bringing increased winds and higher precipitation.

At French Frigate Shoals, data show that the record for maximum sustained wind was 52 knots from east-northeast in December (Amerson 1971). Monthly wind speed averaged higher than the annual mean of 12.6 knots in November-April and lower in March-October.

Seasonal data on prevailing wind direction and speed, shown in

Fig. 14 Figure 14, indicated an easterly component. The mean wind speed in winter reached 14.3 knots with winds high from all directions but highest from northwest to east-southeast and the mean maximum from east-northeast. In spring, the mean wind speed reached 13.1 knots and winds were highest from west to south although the mean maximum was from the northeast. The summer wind speeds, which averaged 11.5 knots, were highest from northeast to east-southeast and the mean maximum was from the east. The change in mean wind speed from summer to autumn was insignificant as autumn winds averaged only 11.6 knots. The highest winds blew from west-northwest and northwest, north through south-southeast, and from the northeast.

In general, climatological data show that Midway's climate was influenced by marine tropical or marine Pacific air masses depending on seasonal changes (Amerson et al. 1974; Clapp and Wirtz 1975). In the summer, the Pacific high predominated, placing the area around Midway under the influence of northeasterly trade winds (Mauck 1975). In the winter, however, especially in November-January, the Aleutian low moved southward over the North Pacific and displaced the Pacific high; the result was that the Kure-Midway area was affected

by prevailing winds from the west and frontal weather. A definitive study of Midway's climate may be found in Mauck (1975).

ig.15 Winter storms in the Midway area were relatively common and brought significant increases in wind and rain especially in September-December (Amerson et al. 1974; Mauck 1975). The prevailing wind was easterly in February-November but westerly in December-January (Figure 15). The wind speed averaged 10 knots annually and the range 5 knots. In July-October, maximum winds blew generally from the east whereas in November-June, they blew from the west. Peak wind speed reached 35-41 knots in May-August and 42-55 knots in September-April. Peak gusts usually occurred in December and January, reaching 77 and 67 knots, respectively.

able 5 At Kure, which lies in the path of the northeast trades from the Pacific subtropical anticyclone most of the year, westerly winds predominate in winter as a result of the position of the island along the southern edge of the Aleutian low (Woodward 1972). Data collected at Kure in 1961-68 showed that in November-February, winds were variable but usually had a strong westerly component. In March-June and September, winds were again variable but the major component during these periods were easterly. The trades usually predominated in July-August when almost all the winds came from the east. Wind speed ranged from 0 to 46 knots and the annual means varied between 4 and 7 knots. The data also showed that the strongest winds usually occurred in winter and early spring and the weakest winds in summer (Table 5).

RAINFALL

Annual precipitation at French Frigate Shoals in June 1954-December 1962 (February 1960 not included) reached an average of 1,150 mm (45.29 in.) (Amerson 1971). Figure 16 shows the mean number of days with measurable precipitation (at least 16 days) each month. It reached 20 or more days in July-August, October, and January and was least frequent in February-June and September. Thunderstorms usually occurred only in April and December. Figure 17 shows the mean monthly precipitation in 1954-62 at French Frigate Shoals. Heaviest rain usually occurred in December-March.

At Midway, data on mean number of days with measurable precipitation (Figure 18) and mean annual precipitation (Figure 19) show that May and June are the driest months of the year (Amerson et al. 1974). Rain or drizzle occurred most frequently in July-February and least frequently in May-June. The annual precipitation in 1953-63 averaged 1,082 mm (42.59 in.) with the monthly maximum of 129 mm (5.07 in.) occurring in January and August, a secondary high of 125 mm (4.92 in.) occurring in October, and a minimum of 52 mm (2.03 in.) occurring in November. Mauck (1975) noted that during the summer, rainfall was usually associated with scattered cumulus buildups of the trade wind region whereas during winter, the heaviest rainfall was associated with frontal passages.

No rainfall data were collected from Kure; therefore, the reader is referred to data from Midway atoll (Table 6).

OCEANOGRAPHIC CLIMATE

In the Hawaiian Islands region, not only the meteorological but also the oceanographic properties show little apparent seasonal variation. Ranging between 22.8° and 25.6°C (73° and 78°F), sea-surface temperatures show relatively small seasonal and year to year changes ([U.S.] Bureau of Commercial Fisheries (BCF) 1963). Surface salinity also varies little seasonally with averages ranging from $34.8^{\circ}/\text{‰}$ to $35.1^{\circ}/\text{‰}$, but in contrast to temperatures, the year to year variations in surface salinity are rather large. The result is that in some years, the change in salinity between seasons is not clearly detectable whereas in others, it may be more than $0.5^{\circ}/\text{‰}$.

ig. 20 The water types and currents of the Pacific are illustrated in Figure 20. A boundary near the Hawaiian region separates North Pacific Central water from the California Current Extension water (BCF 1963). The former has a salinity greater than $35^{\circ}/\text{‰}$; the latter less than $34.8^{\circ}/\text{‰}$. The boundary, therefore, is identified by a relatively small and narrow salinity gradient.

Shifting with the season, this boundary, from a position just south of the Hawaiian Islands during late fall and early winter, moves to one just north of the islands in late summer (BCF 1963). Shifts of longer duration also occur possibly because there is either movement or dilations and contractions of the North Pacific Central system.

SURFACE TEMPERATURE

In oceanography, as in meteorology, temperature has long been recognized as an important climatic character. Seckel (1962) observed that north of the Hawaiian chain, there is a parallel isothermal structure between November and April with latitudinal temperature gradient of about 0.6° to 0.8°C (1.0° to 1.5°F) per degree of latitude (Figures 21a to 21l). A change in this temperature structure first becomes apparent in May followed by a breakdown of the parallel isothermal structure in June. An irregular temperature regime persists in the northern section of the Hawaiian chain in July-September, but in October, the isotherms again become parallel.

Minimum and maximum temperatures generally occur in March and September, respectively (Seckel 1962). Although the minimum sometimes occurs in February and the maximum in August or October, they show no significant differences from those in March and September.

Figure 22, which shows the March and September mean profile in long. 153° - 161°W and in long. 168° - 176°W , demonstrates that the annual temperature range between lat. 10° and 15°N is about 1.4° (2.5°F) both in the eastern and western sections. The range increases to about 5.8° and 6.4°C (10.5 and 11.5°F) at lat. 29°N in the eastern and western sections, respectively.

The mean zonal temperature profiles for March and September show that for these months, the temperature is about 1.7°C (3°F) higher in the western than in the eastern part of the region, except in September in lat. 15° - 20°N and in lat. 20° - 25°N where the increases

g. 23 are 2.2° and 2.8°C (4° and 5°F), respectively (Figure 23) (Seckel 1962). Seckel also showed that the seasonal temperature range between long. 153° and 161°W at lat. 12° , 17° , 20° , and 26°N increased only slightly northward from 1.7°C (3°F) at lat. 12°N to 2.8°C (5°F) at lat. 22°N , but the range almost doubled to 5.3°C (9.5°F) at lat. 26°N (Figure 24).

g. 24

THERMOCLINE DEPTH

Another important feature of the oceanographic climate in the NWHI region is the vertical temperature distribution. The permanent or main thermocline, in which the maximum temperature change occurs and which lies between the surface layer of constant temperature and the deeper layer in which the rate of change of temperature vertically is rather small, is always present in the Hawaiian region (Seckel 1962). Below the mixed layer the average temperature gradient is about 15° , 6° , and 5°C per 100 m (59° , 43° , and 41°F per 330 ft) at lat. 10° , 20° , and 30°N , respectively. Superimposed on the permanent thermocline may be a seasonal thermocline and, in addition, there may also be a diurnal thermocline, which is defined as a small rise in surface temperature of the order of 1°C (1.8°F) extending to a depth of about 10 m (33 ft).

Concerning the depth of the mixed layer in the Hawaiian region, Seckel (1962) observed that in January-February there is a prominent trough in which the depth of the mixed layer is greater than in the surrounding areas extending east to west between lat.

15° and 2°N (Figures 25a to 25d). The depth is generally greater than 76 m (250 ft) and west of long. 165°W it exceeds 122 m (400 ft). But in March-May, the depth of the mixed layer decreases except along the southern boundary east of long. 162°W where it tends to increase.

A new distributional pattern of the depth of the mixed layer is evident in June-August (Seckel 1962). A trough is established at lat. 10°-13°N to the west of long. 156°W where the depth reaches about 91 m (300 ft), whereas to the east of long. 156°W, the trough reaches 61-76 m (200-250 ft). Over much of the area north of lat. 20°N, the mixed layer increases only slightly from less than 30 m (100 ft) deep in June to less than 46 m (150 ft) in July-August. In September, there appears to be a northward movement of a trough which is centered at about lat. 15°N west of long. 160°W with depths 76-91 m (250-300 ft). By October, the trough resumes its winter position. The depth of the mixed layer north of lat. 20°N increases and the beginnings of the typical January-February structure are again visible.

Fig. 26

The primary feature, then, of the distribution of the mixed layer in the Hawaiian Islands region is the presence of a trough and seasonal differences in its location (Figure 26). In January, there is maximum development in the depth of the trough which may exceed 122 m (400 ft) in an east-west direction between lat. 15° and 20°N. The June distribution typifies the other extreme when the trough is found in its southernmost position and its depth is also at a minimum in the northern region. Seckel noted that in the March-May

transition period, the irregular depth distribution suggests disintegration of a pattern rather than a southward movement.

SURFACE SALINITY

Equivalent in importance as a climatic indicator in oceanography is salinity. In the vicinity of the Hawaiian Archipelago, the maximum salinity occurs in November-February and the minimum in July (Seckel 1962). For example, Seckel found that the $35^{\circ}/_{\text{oo}}$ salinity isopleth started a northward movement in April and reached an extreme position in July (Figure 27). The southward movement eventually positioned the $35^{\circ}/_{\text{oo}}$ isopleth at lat. 17° - 19° N, the extreme winter location, in November-February. In April-August, the salinity increases northward from $34.65^{\circ}/_{\text{oo}}$ at lat. 10° N to $34.75^{\circ}/_{\text{oo}}$ at lat. 20° N but only by an average of $0.01^{\circ}/_{\text{oo}}$ per degree of latitude. Figure 28 shows that the salinity then rises at an average rate of $0.13^{\circ}/_{\text{oo}}$ at lat. 23° N. The maximum of $35.35^{\circ}/_{\text{oo}}$ is reached at lat. 28° N, the increase occurring at a rate of $0.04^{\circ}/_{\text{oo}}$ per degree of latitude. Of significance here is the high salinity gradient which can be found within and slightly north of the Hawaiian chain, indicating the presence of a transition zone or boundary between different types of water. In winter, the salinity decreases from $34.3^{\circ}/_{\text{oo}}$ at lat. 10° N to a minimum of $34.2^{\circ}/_{\text{oo}}$ at lat. 12° N, then increases rapidly to $35.05^{\circ}/_{\text{oo}}$ at lat. 19° N at a rate averaging $0.12^{\circ}/_{\text{oo}}$ per degree of latitude (Figure 28).

Seckel (1962) also noted that in April-August, the high salinity gradient between lat. 20° and 25° N is well defined in the eastern region of the Hawaiian Islands (Figure 29a). Of particular interest are two cells in which the salinity is higher than 35.4‰ . In November-February (Figure 29b), the salinity gradient near the southeastern region of the Hawaiian Islands has moved northwestward and the gradient formerly in the area has shifted southward.

Seckel (1962) concluded that to the north and south of the Hawaiian Islands, low and high salinities occur about the same time as low and high temperatures. In the vicinity of the Hawaiian Islands, however, low and high salinities occur about 3 months after the time that the mixed layer reaches its minimum and maximum depths, respectively. Finally, Midway Island is located near the salinity maximum; the sharp decline of about 0.35‰ in July in this region may be due to either a southward or a northward displacement of the high salinity cell. Seckel further postulated that in spring, the high salinity boundary moves northward east of long. 165° W and northwestward west of long. 165° W reaching Midway in July.

SURFACE CURRENTS

The NWHI lie in an area of the Pacific where no major current system passes through them. Sverdrup, Johnson, and Fleming (1946) reported that part of the water in the North Pacific Current, which has a general eastward flow, appears to turn southward before reaching

long. 150°W and only a small portion continues to flow southward between the Hawaiian Islands and the west coast of North America. The main part of the North Pacific Current, therefore, turns back toward the west near the Hawaiian Islands.

A major feature of this North Pacific gyre is the Subtropical Convergence which marks the region of weak horizontal flow and where water tends to pile up and thicken the surface layer as a result of water accumulation. Sverdrup et al. (1946) observed that the position of the convergence changes from north to south with the season and may even shift from year to year so that under certain conditions the Hawaiian Islands may lie inside or outside the gyre.

ig. 30 Generally, the main surface currents in the NWHI region flow westward or northwestward in summer (Figures 30a and 30b) (June 1951). Between Lisianski and Pearl and Hermes Reef, however, the flow appears to be northward at this time. In winter, the current flow tends to be southeastward from Midway to Gardner Pinnacles. There is a tendency for the current to flow southward most of the year in the vicinity between Midway and Kure atolls. Shown in Figures 31a to 31l are charts of monthly surface currents and temperatures around the Hawaiian Archipelago (see Appendix 1 for explanation).

ig. 31

BOTTOM TOPOGRAPHY

From an oceanographer's point of view, the chief interest in the topography of the sea floor is that it forms the lower and lateral

boundaries of water. The fishery biologist's chief interest in bottom topography, however, is that it shows the locations of fishable grounds. Figures 32a to 32l are graphic representations of the bottom topography in the area around the Hawaiian chain (enclosed in heavy lines in Figure 33). They show the trenches, troughs, fracture zones, ridges, banks, and seamounts. The banks and seamounts are of particular interest because the Japanese and Russians have established a trawl fishery for pelagic armorhead, Pentaceros richardsoni, and alfonsin, Beryx splendens, which adopt a lifestyle associated with tops of seamounts.

Within the NWHI region, there exists a series of shallow-water banks, which vary from about 1.5 km (1 mi.) to over 80 km (50 mi.) in length and which lie amongst various islands in this group (June 1951). Whereas the water depth over these banks are between 16 and 73 m (9 and 40 fathoms) the troughs between the banks and islands may be as deep as 1,830 m (1,000 fathoms). June observed that along the northern and southern boundaries of the NWHI chain, the 3,660-m (2,000-fathom) contour is usually within 37 km (20 mi.) of the shoals.

PLANKTON

In the Pacific Ocean, zooplankton volume is distributed in a similar fashion as PO_4-P (Reid 1962). The volumes are usually high in the eastern boundary currents, low in central water, and relatively

high along the equator and in two zones north and south of the equator associated with the equatorial divergence (Figure 34).

From studies conducted by King and Demond (1953) in the central Pacific, it was shown that the greatest abundance, both by number and volume, of zooplankton occurred near the equator. Figure 35 shows the variation in temperature, salinity, oxygen, inorganic phosphate, thermocline depth, and zooplankton volume along long. 158° and 172°W in June-August 1950. In examining differences among the mean zooplankton volume among latitudes, King and Demond demonstrated that there were significant differences ($P < 0.02$) among the means for latitudes. For example, along long. 172°W, not only zooplankton volume but also the estimated numbers per cubic meter of water strained tended to be low in the higher latitudes around the NWHI and high near the equatorial region.

MARINE RESOURCES

Very little is known about the marine resources of the NWHI. Most of what is known about them comes from observations made during research cruises by several agencies and from data collected by foreign fishing vessels. The sections that follow present some of the published and until now unpublished results obtained by research and commercial vessels that were engaged in assaying the fish stocks in waters of the NWHI.

BIRD FLOCK AND FISH SCHOOL SIGHTINGS

The chief interest in sightings of bird flocks and fish schools is in obtaining some indication of the density of fish schools in a given area. For example, because pole-and-line and purse seine fisheries for tuna are wholly dependent on the presence of surface schools, it is highly desirable to have some index of relative abundance of tuna schools on the fishing grounds.

Although there is no established commercial fishery for surface schooling tunas in the NWHI region at the present time, there are sufficient reliable reports of tuna schools sightings--based on several exploratory fishing cruises--and reports of Japanese fishing vessels operating within the waters of the NWHI to indicate the presence of commercial concentrations of yellowfin tuna, Thunnus albacares, skipjack tuna, Katsuwonus pelamis, and kawakawa, Euthynnus affinis.

Most of the bird flock and fish school sightings in the NWHI region occurred near land. Murphy and Ikehara (1955), who summarized sightings of bird flocks and fish schools in the NWHI, noted that the sightings were predominantly within 110 km (60 mi.) of the islands and very few schools in the semioceanic area (110 and 330 km or 60 and 180 mi. from land) (Tables 7a and 7b). Waldron (1964) observed that the rate of sightings in the NWHI area was highest in March-May and in June-August, periods which overlap the May-September skipjack tuna fishing season in Hawaiian waters. The rate of sightings in waters of

the NWHI was similar to that for Hawaiian waters and was at times considerably higher.

Charts summarizing sightings of bird flocks, skipjack tuna schools, and total fish schools by time-area units bounded by lat. 30°S and 30°N, and long. 110°W and 120°E are shown in Figure 36a through 36l.³

COMMERCIAL FISHING OPERATIONS

As early as June 1946, commercial fishing vessels operating out of Honolulu began fishing in waters of the NWHI (Amerson 1971). Establishing a fishing base at French Frigate Shoals, Hawaiian commercial fishermen enjoyed good fishing and the catches, air shipped to Honolulu by chartered plane, were large enough to make the operation profitable.

By early November 1946, two companies--the Hawaiian American Fisheries, headed by Louis K. Agard, Jr., and the Seaside Fishing Company, run by Frank Opperman and Warren Haines--established fishing bases on Tern Island at French Frigate Shoals and used a chartered DC-3 from Trans-Air Hawaii to transport the catch to markets in Honolulu (Amerson 1971). Most of the catches consisted of fish taken by traps; however, a large proportion of the landings consisted of green sea turtle, which was also a profitable commodity.

³Naughton, J. J. Bird flock and surface tuna school sightings in the central Pacific Ocean, 1950-72. Manuscript in preparation. Western Pacific Programs Office, Southwest Region, National Marine Fisheries Service, NOAA, Honolulu, HI 96812.

The joint venturers involved in this newly developed fishery, however, eventually encountered difficulties in keeping the operation viable (Amerson 1971). In an attempt to reduce costs and increase profits, Hawaiian American Fisheries acquired new partners and formed a new corporation--Aero Fisheries--with a plane of its own. One flight was completed in July 1949. Mechanical problems with the plane and lack of financing to continue the plane operation forced Aero Fisheries to abandon its NWHI fishing operation.

Several other attempts to revive the fishing in the NWHI during the 1950's met with varying success. In 1959, Agard formed another joint venture and even purchased a refrigerated vessel and a plane to transship the catches. This venture was also short-lived.

HANDLINE FISHING

Some commercial fishing operators still believe that an efficiently run operation in the NWHI could be profitable, but others maintain a cautious attitude about the possibility of developing the fishing potential in these waters. Commercial deep-sea fishing vessels, using handline, lobster traps, and trolling gear, make periodic trips to waters around Nihoa and Necker Islands and enjoy relatively good fishing. Maintaining the catch in marketable condition, once a serious obstacle to further expansion of the fishery appears to be somewhat less of a problem today as modern methods of fish handling have reduced spoilage. The catches made by these vessels

around Nihoa and Necker, by type of gear used in 1966-75 and the value of the catch, are given in Table 8.

Among the species that contribute a large proportion to the catches of the commercial vessels fishing NWHI waters are sea bass, jack crevally, amberjack, and pink, gray, and red snappers. Figure 37, which shows the annual handline catches and value of the species from Necker Island, indicates landings were 22,000 kg or less in 1966-69. In 1970, however, the total landing increased significantly, nearly doubling from about 18,000 to 34,000 kg. Catches since then have fluctuated widely and show a slight downward trend from 33,000 kg in 1971 to 27,000 kg in 1975. The values, which rose precipitously in 1970, have also fluctuated widely between \$40,000 and \$65,000.

Exploratory handline fishing was also attempted during a research cruise of the Townsend Cromwell (cruise report, Townsend Cromwell cruise 67, October 20, November 26, 1975). Fourteen handline stations in depths of 26-100 m (14-55 fathoms), occupied at various locations in waters of the NWHI, yielded catches dominated by Carangoides ajax, Caranx cheilio, Pristipomoides microlepis, Seriola dumerilii, and Epinephelus quernus. The largest handline catches were made near Gardner Pinnacles where 11 C. ajax totaling 181 kg (400 lb) were taken and at Laysan Island where 33 C. ajax weighing a total of 293 kg (645 lb) were captured during 3 h of fishing with five handlines.

POLE-AND-LINE FISHING

At present, there is no established fishery for the surface schools of tuna occurring in waters of the NWHI. The frequency of bird flock and fish school sightings made during several exploratory cruises to the area, however, gives an indication of the relative abundance of surface fish schools. Furthermore, the fact that Japanese pole-and-line fishing vessels have been observed actively fishing in NWHI waters attests to the potential of the area as a tuna fishing ground. For example, on July 11, 1976, four Japanese pole-and-line fishing vessels were sighted within 22 km (12 mi.) of Laysan Island; two were actively fishing with pole and line for skipjack tuna (William Streeter, Western Pacific Programs Office, Southwest Region, National Marine Fisheries Service, NOAA, Honolulu, HI 96812, pers. commun.). At the time of sighting, one vessel had already taken 907 kg (2,000 lb) of skipjack tuna. Subsequent sightings included not only pole-and-line fishing vessels but also longline vessels as well as Soviet trawlers.

The paucity of data on pole-and-line catches by research vessels of NMFS (including its predecessor agencies, Pacific Oceanic Fishery Investigations and Bureau of Commercial Fisheries) during cruises in waters in the vicinity of the NWHI makes it difficult to evaluate the effectiveness of this type of fishing. Data for 26 schools, however, have been examined; the catch rates for these schools which included both skipjack and yellowfin tunas, averaged 1.33 fish per hook-minute. Not all the data collected give an

indication of biting rate. Several schools were fished primarily to obtain fish for tagging experiments. Therefore, the catch rates are not indicative of actual biting rates.

Past reports on the availability of live bait in the NWHI pointed to the existence of some productive baiting grounds (Eckles 1949; Smith and Schaefer 1949; June 1951). For example, Smith and Schaefer reported catching 437 scoops (4.5 kg per scoop) of silverside, Pranesus pinguis, locally called iao at French Frigate Shoals. The silverside is a hardy baitfish and suitable for long-distance transport in the baitwells of tuna fishing boats; however, although this species is the best baitfish found in the NWHI, June and Reintjes (1953) observed that its abundance fluctuates markedly. On one particular cruise of the RV Charles H. Gilbert, which operated in waters of the NWHI during a skipjack tuna tagging experiment, only 27 buckets (5.4 kg per bucket) of iao were taken in 2 days of baiting (Narrative Report, Charles H. Gilbert, cruise 114, April 19-May 29, 1969).

TROLLING

Trolling offers an alternative to the ways pelagic surface schooling fish such as tunas and tunalike fishes can be captured in waters of the NWHI. Not requiring live bait, trolling is used extensively in the fishery off the U.S. west coast for albacore, Thunnus alalunga. For capturing other species of tunas, however, it has never attained a position of major importance.

In the normal course of steaming through waters of the NWHI during exploratory cruises, research vessels of the NMFS used trolling gear as an incidental procedure. The troll catches made over the years from 1954 to 1964 are summarized in Table 9. Troll catches made by commercial vessels operating in the NWHI are shown in Table 8.

The data available are meager and do not provide a definitive pattern of the availability and relative abundance of the various species taken in the NWHI. In terms of temporal distribution of the catches, however, it appears from the data that skipjack tuna, yellowfin tuna, kawakawa, and, in particular, mahimahi, Coryphaena hippurus, tend to be more available and vulnerable to the gear in April-August than in other months of the year.

LONGLINE FISHING

The Japanese high-seas longline fishery for deep-swimming tunas began in 1950 as part of a postwar recovery plan. Subsequent expansion of the longline fishing grounds was phenomenal and by 1954, Japanese longliners were operating in a large part of the Pacific as fishing operations extended from the Japanese coast eastward as far as long. 135°W (Figure 38).⁴ The continued search for new fishing ground eventually extended to long. 105°W. By 1962, Japanese longliners were operating throughout the tropical and subtropical waters of the Pacific Ocean (Figure 39).

⁴ Shomura, R. S., and R. N. Uchida. Pelagic fishes and fisheries of the Indian Ocean. Paper presented at the Biological Seminar of the Cooperative Investigations in the North and Central Western Indian Ocean, Nairobi, Kenya, 25 March-1 April 1976.

To get an estimate of the amount of fishing effort being exerted by Japanese longliners near the Hawaiian Islands, data from "Annual report of effort and catch statistics by area on Japanese tuna longline fishery" were extracted and summarized for the area bounded by lat. 20° - 30° N and long. 160° W- 180° . The percentage of the North Pacific longline fishing effort expended within the NWHI region by Japanese longliners in 1963-73 is given in Table 10, together with catches and percentages for tunas and billfishes.

In 1964-73, only about 2% of the entire Japanese longline fishing effort in the North Pacific were expended within the NWHI region (Figure 40). The data show that nearly 3% of the North Pacific effort were expended in this area in 1964, but the proportion declined to 0.6% in 1966. Since then, however, the proportion increased irregularly and peaked at 3.3% in 1970. In 1971-73, it fluctuated around 2.5%.

Albacore, which was the first species of tuna to be intensively exploited by the Japanese longline fishery in the North Pacific, is by far, the most important tuna species taken within the NWHI region by Japanese longliners. Figure 41 shows the percentage of the North Pacific catches of tunas and billfishes, by species, taken within the NWHI region by the Japanese. Albacore and bigeye tuna, Thunnus obesus, from near Hawaii accounted for about 2% of the entire North Pacific catch of these species. The proportion, however, has increased in recent years, fluctuating between 2% and 4%. Whereas albacore is not an important component of the Hawaiian longline

catch, bigeye tuna is one of the major species of the Hawaiian longliners. Hida (1966) has shown that the Japanese longline fishery has been a causative agent in reducing the catch of bigeye tuna by the Hawaiian longline fleet.

Among billfishes, striped marlin is the most important species of the Japanese longliners within the NWHI region; however, it does not appear that the proportion taken near the NWHI has increased relative to the North Pacific catch of this species by Japanese longliners.

TRAWLING

Of all the methods that are used to exploit the fish resources of the NWHI, trawling is potentially one of the most important, particularly over the numerous banks and seamounts or guyots (banks are usually sizable and appear somehow to have become detached from the flanks of continents and now stand like great underwater mesas; seamounts or guyots are submerged volcanoes that are several hundred meters below the water level and which have flat tops, probably as a result of the erosive action of the surf).

The discovery of pelagic armorhead and alfonsin on seamounts northwest of Midway was made by a commercial trawler of the Soviet Union in November 1967 (Sakiura 1972). Almost immediately after the discovery, Soviet trawlers worked the banks and seamounts of the Emperor Seamount range. Subsequent surveys by Soviet research vessels

were made closer to the Hawaiian Islands, including Kinmei Bank and Milwaukee Bank both outside the U.S. zone of extended jurisdiction, and Hancock Seamount inside the zone.

Fishing over seamount tops that were from 100 to 400 m below the sea surface, the Soviet trawlers found schools of armorhead averaging 30 m in thickness and produced catches varying from 3 to 50 metric tons (MT) on 10- to 20-min hauls. Often, the catches were as much as 30 MT in a 10-min haul. Sakiura (1972) reported that the Soviet trawlers produced 133,400 MT of armorheads from these seamounts between December 1969 and July 1970.

In 1969, the Japanese started deepwater trawling over seamounts and banks in the central North Pacific, north of Midway atoll. Working the grounds for pelagic armorhead, alfonsin, and a species of rockfish, Sebastes matsubari, the Japanese trawlers made fairly good catches. On one particular trip made from mid-June to early August 1975, one trawler reported catching 280 MT of fish valued at US\$220,000 over the seamounts (U.S. NMFS 1975). Although armorhead first encountered consumer resistance when first marketed in Japan about 6 years ago, the species gradually gained consumer acceptance. By early 1975, an upsurge in demand brought about a renewed intensity in fishing for this species.

There appears to be some indication that the seamount resource of armorhead has started to decline. Three Japanese trawlers, fishing for this species off Midway atoll reported an average catch of 30 MT per day, considerably less than the break-even level of 40 MT per day

(U.S. NMFS 1976). These Japanese trawlers reported that armorhead landings in this area have declined sharply since early April when a Soviet trawling fleet worked the same grounds for armorhead.

More recent data on trawling operations in waters of the NWHI are also available from research cruises (Cruise Report, Townsend Cromwell, cruise 67, October 20–November 26, 1975). The Cromwell, which operates out of Honolulu, Hawaii, has conducted demersal resource surveys in the vicinity of Middle Bank, Nihoa, Necker, St. Rogatien Bank, Gardner Pinnacles, Pearl and Hermes Reef, Kure, Lisianski, and Laysan Islands. Using a high opening "Norwegian" fish trawl, which has a 19.2-m (63-ft) headrope, 25.3-m (83-ft) footrope, 10.2-cm (4-in.) diameter roller line, 10.2-cm (4-in.) mesh body and cod end, 3.8-cm (1.5-in.) mesh cod end cover, and 340.2-kg (750-lb) steel, V-doors, the Cromwell made several "blind" tows, which varied from 10 to 60 min and which caught a large variety of fish.

At Middle Bank, which has a depth of 62 m (34 fathoms), catches were dominated by three species of Acanthuridae--Naso brevirostris, N. hexacanthus, and N. lopezi, a small serranid, Caesioperca thompsoni, and the introduced lutjanid, Lutjanus kasmira. Catch rates ranged up to 110 kg/h (243 lb/h) for Naso spp., 129 kg/h (285 lb/h) for C. thompsoni in the small mesh cod end cover, and 41 kg/h (90 lb/h) for L. kasmira. The zooplanktivorous and herbivorous fishes constituted from 40% to 91% of the trawl catches at this locale. From the four daylight hauls at Middle Bank, total catches varied from 33 to 230 kg (48 to 507 lb), which when extrapolated indicate catch rates of 44–414 kg/h (96–913 lb/h).

and an average catch rate of 242 kg/h (534 lb/h). Assuming that the trawl sampling width was 11.5 m (about 38 ft), the Cromwell's scientists calculated that the standing biomass at Middle Bank is 855-8,137 kg/km² and the mean, 4,680 kg/km². These values compare favorably with estimated densities of demersal stocks in the region of the South China Sea, which is considered one of the most productive fisheries region of the world with densities ranging from 1,250 to 5,000 kg/km².

Five trawl stations occupied by the Cromwell north of Nihoa Island also yielded good catches. The catches, which varied from 83 to 158 kg/h (184 to 349 lb/h) and averaged 117 kg/h (258 lb/h), indicated a standing biomass of 1,011-2,074 kg/km². Catches at Nihoa Bank, which is relatively shallow at 48-55 m (26-30 fathoms), were dominated by N. brevirostris, N. hexacanthus, and Acanthurus olivaceus. Zooplanktivorous and herbivorous species constituted from 38% to 84% of the catch.

At a depth of 29-48 m (16-26 fathoms) near Necker Island, two daylight hauls by the Cromwell yielded relatively poor catches. A single night tow, however, produced a catch equivalent to a rate of 512 kg/h (1,129 lb/h) and to a standing biomass of about 8,028 kg/km². Although a variety of species was caught at this location, N. hexacanthus was again the dominant species. Trawl catches from deeper areas around Necker Island were very poor as were those made on St. Rogatien Bank.

Scientists aboard the Cromwell also surveyed waters of the NWHI with a 12.5-m (41-ft) headrope, semiballoon shrimp trawl at depths of 29-37 m (16-20 fathoms) and in deeper waters ranging from 400 to 785 m (218 to 430 fathoms). Catches were small; the deeper hauls produced the caridean shrimps, Heterocarpus ensifer and H. laevigatus, at the rate of 0.7-0.9 kg/h (1.5-2.0 lb/h).

TRAP FISHING

Both fish and shrimp traps have been fished experimentally in waters of the NWHI. On cruise 67 of the Townsend Cromwell, exploratory fishing was conducted with two sizes of fish traps and shrimp traps. The fish traps were of two general types--large traps which measured 1.5-m (5-ft) square, 1.2-m (4-ft) high, and with two bottom and one upper opening, and small traps which measured 0.6 x 0.6 x 1.2 m (2 x 2 x 4 ft) and had either one or two entrances. The traps, baited with 0.4-2.3 kg (1-5 lb) of chopped fish in 13-mm (0.5 in.) wire mesh containers secured to the bottom of the traps, were fished overnight for 13-16 h at depths ranging from 29 to 119 m (16-65 fathoms).

The trap catches were quite variable and generally small. Snappers, locally called "opakapaka," Pristipomoides microlepis, were caught in fair numbers on four occasions in the large traps that were fished at the shelf edge north of Necker Island in 44-57 m (24-31 fathoms) of water. Catches ranged from 4.5 to 7.7 kg (10 to 17 lb)

per set and averaged 514 kg (11.9 lb). Near Kure atoll, one trap, fished at 48 m (26 fathoms) produced 18.4 kg (40.5 lb) of carangids, Caranx cheilio. Two traps out of 12 that were fished at Lisianski Island produced 16 and 48 kg (35 and 105 lb) of another species of carangid, Carangoides ajax.

Catches of lobsters were also variable. At a locale north of Necker Island, 17 traps fished at 29-57 m (16-31 fathoms) produced 160 lobsters, Panulirus marginatus, which averaged 0.6 kg (1.4 lb). Traps fished near the edge of the bank in 44-57 m (24-31 fathoms) of water produced the best catches. At a station north-northwest of Nihoa Island, the traps, fished in 44-48 m (24-26 fathoms) of water produced fair numbers of lobsters. Here, the 11 traps yielded 41 lobsters which averaged 0.9 kg (2.0 lb). Catches were relatively poor at stations occupied near Pearl and Hermes Reef, Kure Island, Lisianski Island, Laysan Island, and Gardner Pinnacles. The commercially valuable kona crab, Ranina serrata, occurred in traps set in 46-55 m (25-30 fathoms) of water off Pearl and Hermes Reef and Kure Island. Three traps at Kure produced 4.5-27.2 kg (10-60 lb) per trap or an average of 13.9 kg (30.7 lb) per trap.

Six shrimp traps set overnight in depths of 475 and 549 m (260 and 300 fathoms) on two occasions off Necker Island, produced 16.6 kg (36.5 lb) of Heterocarpus laevis (18-20 shrimps per kilogram or 8-9 shrimps per pound, head on). Four traps fished off Nihoa Island yielded 11.0 kg (24.2 lb) of H. laevis and 2.0 kg (4.3 lb) of H. ensifer.

SURVEY OF NEARSHORE FISHERY RESOURCES

During cruise 76-04-71 of the Townsend Cromwell (Narrative Report, Townsend Cromwell, cruise 76-04-71, May 3-June 9, 1976) the nearshore and shoreline fishery resources were surveyed by personnel of the Hawaii Division of Fish and Game at Nihoa Island, French Frigate Shoals, Laysan Island, and Necker Island. Data on species composition, distribution, and densities of fishes at each of these locales, collected through shoreline, surface, and underwater

Tables 11,12 observations, are given in Tables 11 and 12.

The preliminary results indicated that the carangids, locally called "ulua," and sharks, Carcharhinidae, were large and relatively abundant in certain areas. Other families such as Holocentridae, Apogonidae, Pomacentridae, Chaetodontidae, Acanthuridae, and Muraenidae, commonly associated with similar habitats in waters surrounding the major Hawaiian Islands, appeared to be noticeably absent in the communities observed. The low diversity of fish species present within the nearshore area surveyed may be the result of the presence and abundance of large predators. Estimated fish density, given in Table 13, was highest at Whale-Skate Island at French Frigate Shoals. Here, Mulloidichthys samoensis, Carangoides ajax, and Scarus perspicillatus, occurred in greatest densities.

Table 13

SIZE OF FISH AND LOBSTERS

No definitive study has been made on the size composition of the various species of fish caught in waters of the NWHI. The segment of the population that the deep-sea handline fleet samples is not documented. The reader is, therefore, referred to Gosline and Brock (1960) for information on size of the various handline-caught species. For nearshore fishes, surveys by the Hawaii Division of Fish and Game indicate that species observed were predominantly in the maximum or near-maximum size classes at Nihoa, French Frigate Shoals, Laysan, and Necker. Furthermore, they noted that the relative absence of juveniles was particularly striking (Narrative Report, Townsend Cromwell, cruise 76-04-71, May 3-June 9, 1976).

Table 14

Concerning the species taken in the Japanese trawl fishery, data from the 1972 North Pacific seamount surveys of the RV Kaiyo Maru were used (Japan Fisheries Agency 1974b). Table 14 shows that at Hancock Seamount, the alfonsin taken on one of the tows varied from 23.2 to 33.6 cm and averaged 27.1 cm. The average weight was 428 g. Armorhead taken in several tows at the same seamount varied widely in size from 21.0 to 38.3 cm; the average size calculated for each tow ranged between 26.8 and 27.7 cm in length and between 291 and 356 g in weight.

Fig. 42

Size distribution of skipjack tuna and kawakawa taken by pole-and-line fishing during NMFS cruises in NWHI waters are shown in Figure 42. Sizes varied widely from 29 to 82 cm in skipjack tuna

and from 38 to 64 cm in kawakawa. The data for skipjack tuna were collected in February, April-July, and September-November and, therefore, represent a fairly good sampling of the size of skipjack tuna that occur in that area. Large, "season" skipjack tuna were encountered in April, May, July, and September which coincides with the time of occurrence of the large fish in waters around the major Hawaiian Islands.

Other species of tuna also were taken, but the samples were too small to be of any value. Briefly, the yellowfin tuna caught by pole and line varied from 44 to 82 cm and frigate mackerel, Auxis thazard, varied from 29 to 41 cm. Among troll-caught fish, the size range were as follows: skipjack tuna--16 to 80 cm; kawakawa--32 to 77 cm; yellowfin tuna--48 to 87 cm; and albacore--52-98 cm.

Among lobsters taken in traps near Nihoa, Necker, Gardner Laysan, and Kure, the females were considerably smaller than the males. Figure 43 shows the percentage weight-frequency distribution of male and female lobsters taken at these locales and for 71 females sampled, the weights varied between 202 and 1,151 g and averaged 256 g. Among 128 male lobsters, however, the range in weights was larger, varying from 205 to 1,374 g and averaging 692 g.

Fig. 43

OBSERVATIONS ON TURTLES, SEAL, AND DOLPHINS

At the intensity with which harvesting was being carried on a few years ago, the green sea turtle, Chelonia mydas, faced the

possibility of complete extirpation. Presently, however, there is confidence among scientists that the species is in no such danger. Instead, there is even the prospect that the green sea turtle will become a resource of major importance. In this respect, the NWHI, a wildlife sanctuary, provide undisturbed breeding grounds not only for turtles but also the Hawaiian monk seal, Monachus schauinslandi. In the sections that follow, some observations made on turtles, seal, and dolphins in the various islands and atolls of the NWHI are discussed.

FRENCH FRIGATE SHOALS

Only the green sea turtle is known from French Frigate Shoals (Amerson 1971). The species is a common resident breeder with nests on the six major sand islands. The object of a commercial fishery in 1946-48, the green sea turtles were abundant at French Frigate Shoals and two Honolulu-based fishing companies established a base at Tern Island. The abundance gradually declined, more as a result of human disturbance than actual killing and harvesting was eventually abandoned. The USFWS reported that commercial fishermen again caught turtles from the atoll in the spring of 1957 (Narrative Report, Hugh M. Smith, cruise 39, April 19-May 30, 1957).

Among the Hawaiian Islands, French Frigate Shoals support the largest population of green sea turtles (Amerson 1971). They occur the year round although the adult population is lowest in the fall, winter, and early spring. The population density increased in

late spring and summer coinciding with breeding. Copulation occurs in early May, nesting commences later the same month, and egg laying has been reported to occur in August-September. Hatchlings probably appear in late July and are common in August and early fall.

GARDNER PINNACLES

The green sea turtle has been reported from waters around Gardner Pinnacles (Clapp 1972). The species does not breed there because the island does not afford a suitable reproductive habitat.

The Hawaiian monk seal, first recorded from Gardner Pinnacles in 1826, appears quite regularly in waters and along the shore of this island (Clapp 1972). There is, however, no evidence that breeding occurs there.

LAYSAN ISLAND

Laysan's mammalian fauna is limited to one species, the Hawaiian monk seal, which uses the sandy beaches for hauling grounds. Considered numerous at one time, the Hawaiian monk seal was hunted almost to extinction during the last half of the 19th century (Ely and Clapp 1973). Legislation to protect the population has increased their numbers until the species has once again become a regular part of the Laysan fauna.

The green sea turtle, using Laysan as a hauling ground, occur in relatively small numbers and probably only a few breed there (Ely and Clapp 1973). Although abundant at one time during the 19th century, they were heavily harvested; the result is that there has been little increase in the population since then.

LISIANSKI ISLAND

The Hawaiian monk seal and the green sea turtle have been recorded from Lisianski, but their abundance has been reduced considerably in the late 1800's and early 1900's as a result of predation by sealers (Clapp and Wirtz 1975). The Hawaiian monk seal is a common breeder at this island and occur throughout the year. Kenyon (1972) has suggested that the decline of populations of monk seals on Midway and Kure Islands was probably due to excessive disturbance by man. Recent population studies suggested that there has not been any decrease in the productivity of the Lisianski population. Clapp and Wirtz observed that about 30-40 pups are produced annually. Peak pupping season appears to be from about March through May-June.

The green sea turtles were once a conspicuous and numerous component in the Lisianski fauna but recent observations indicate a large decrease in numbers since about 1923 (Clapp and Wirtz 1975). This decrease has been attributed to poaching by fishermen in the decade after the Tanager expedition. Clapp and Wirtz also reported

that the number of green sea turtles currently at Lisianski is undoubtedly higher than the maximal count but it is doubtful that the breeding population, if one exists, consists of more than a few individuals. There has been no recent reports of nests or sightings of hatchlings. The presence of rather small turtles at Lisianski also suggests that many are visitors, probably from French Frigate Shoals, the primary breeding ground and from Pearl and Hermes Reef.

PEARL AND HERMES REEF

From Pearl and Hermes Reef, three marine mammalian species have been reported--the Hawaiian monk seal, the Hawaiian spinner dolphin, Stenella roseiventris, and the bottle-nosed dolphin Tursiops truncatus (Amerson et al. 1974). The Hawaiian monk seal, found on most of the NWHI is a resident breeding species present at Pearl and Hermes Reef the year round. A visitor to the NWHI, the bottle-nosed dolphin appear to be regularly associated with shallow waters from French Frigate Shoals to Kure Island. One of the early sightings of this species was made on March 1956 when personnel aboard the RV John R. Manning recorded three large bottle-nosed dolphin on the western side of Pearl and Hermes Reef. The Hawaiian spinner dolphin, on the other hand, although common in Hawaiian waters, appear to be only an occasional visitor to Pearl and Hermes Reef. Eight of them were sighted offshore from Southeast Island on March 1968.

Only one reptile, the black turtle, Chelonia agassizi, has been recorded from Pearl and Hermes Reef (Amerson et al. 1974). There is no substantiated record of sightings of the Pacific hawksbill turtle, Eretmochelys imbricata, from Pearl and Hermes Reef. The black turtle, although uncommon, is a resident breeder at Pearl and Hermes Reef and a few are probably present the year round. The species have been reported to frequent Little North, North, and Southeast Islands.

KURE ISLAND

Two species of turtles--the hawksbill and green sea turtles--have been recorded from Kure Island, although the validity of the sightings of hawksbill turtle is uncertain (Woodward 1972). Most of the sightings, although infrequent, occurred in the lagoon or outside the reef.

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U.S. Navy Hydrographic Office
1950

NORTHWESTERN PACIFIC OCEAN

SURFACE CURRENTS AND TEMPERATURES

Appendix 1

SOURCE OF INFORMATION

The information relating to monthly surface currents shown on this chart was compiled from observations made during the month for all years prior to 1935 by the co-operating observers of the Hydrographic Office. Observations were not considered reliable where tidal currents prevailed; where winds, sea, or swell of force 6 or above were recorded; where the vessel's draft or trim would cause excessive leeway; or when doubt existed as to the meaning of the entry "Nil" on the current report. All current calculations are based on the MEDIAN POSITION method; namely, each observation is applied at only one point, that point being midway between the beginning and end of the ship's run for which the current observation was made.

RESULTANT CURRENTS

The black arrows and numerals show the mean direction and force of the surface current in each 1-degree quadrangle for the month under average normal conditions. The accuracy of the resultant current in any quadrangle is necessarily determined by the number of observations used in the computation. The Hydrographic Office considers a resultant to be fairly accurate if computed from five or more observations in an area of 3,600 square miles. But on this chart all reliable information is shown, for the benefit of the navigator, even where less than the desired five observations were obtained.

The resultant currents in each 1-degree quadrangle are shown as follows: The number in the upper right hand corner of the quadrangle represents the total current observations used in the computation. The numerals in the lower left hand corner of the quadrangle give the resultant drift in miles per day to the nearest tenth of a mile. The direction of the arrow in the center of the quadrangle shows the resultant set.

PREVAILING CURRENTS

The current roses shown in green on this chart were computed from the same information as the 1-degree resultants shown in black. The eight-point rose presents a graphical picture of the frequency of direction and the average drifts within the directions for each area outlined by the heavy brown lines.

The arrows point in the direction towards which the current sets. When the frequency of direction is less than 5 percent, no arrow is shown. The length of the arrow, from the base of the arrow head to the inner edge of the circle, when placed on the attached frequency scale gives the number of times in each 100 observations that the current has been setting in or near the indicated direction. In instances where the full length of the arrow cannot be shown, the shaft is broken and the true percentage inserted in numerals within the break. The width of the shaft when placed on the attached drift scale gives the average drift in knots. The numeral in the center circle gives the percent of "nils" (no appreciable current observed). The approximate number of observations from which the current rose was computed can be obtained by adding the number of observations within the 1-degree quadrangles covered by the rose.

For example the attached rose should be read as follows:

Of the currents observed; 5 percent were setting northeast, the average drift was between 0.33 and 0.66 of a knot; 5 percent were setting east, the average drift was between 0.33 and 0.66 of a knot; 9 percent were setting southeast, the average drift was less than 0.33 of a knot; 5 percent were setting south, the average drift was between 1.33 and 1.66 knots; 57 percent were setting west, the average drift was between 0.67 and 1 knot; 5 percent were setting northwest, the average drift was less than 0.33 of a knot. The percent of "nils" was zero.

SEA TEMPERATURES

The monthly mean sea surface 5-degree isotherms shown in ~~VAGENTA~~ were compiled from the same source and for the same period as the resultant currents shown on this chart.

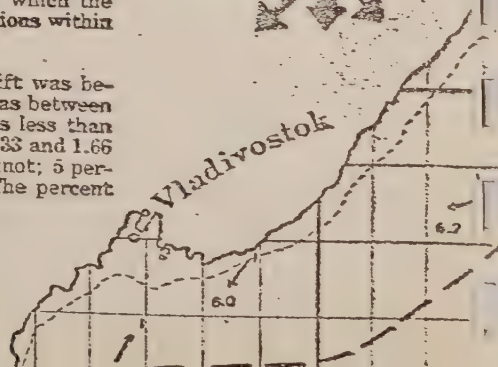
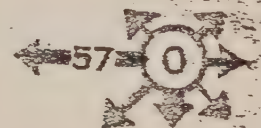
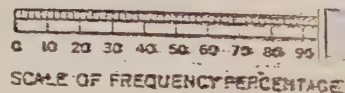
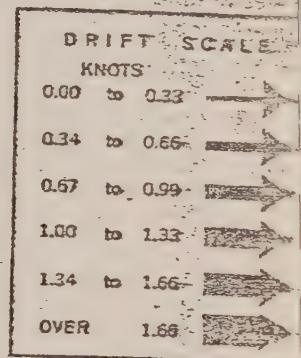


Table 1.—The area in sq. mi., not otherwise in, of the islands and atolls
in the Hawaiian archipelago. (Linslet 1881; Carlquist 1890;
American 1897; Foreman 1898.)

Mauck 1975
Table 2

MONTH	MAXIMUM	MINIMUM	MEAN
JAN	74.2	56.4	66.0
FEB	74.1	56.6	65.9
MAR	74.8	57.0	66.5
APR	76.4	59.2	67.9
MAY	80.3	62.7	71.3
JUN	83.2	66.8	76.0
JUL	84.0	69.3	78.0
AUG	85.1	70.3	79.0
SEP	86.0	70.2	78.9
OCT	83.3	66.0	75.7
NOV	80.3	62.1	72.1
DEC	76.8	58.0	68.4

Table 2.--Maximum, minimum and mean air temperatures, by month, at Midway Atoll, (1949-72 (Mauck 1975)).

Woodward 1972

	January	February	March	April	May	June				
1961	-	-	-	71.9 (68-78)	69.1 (57-75)	74.5 (67-83)	73.5 (65-86)	81.6 (74-88)	84.2 (79-87)	82.8 (77-88)
1962	69.3 (59-73)	68.0 (63-72)	70.1 (62-76)	70.8 (66-74)	71.4 (62-76)	71.9 (65-76)	69.9 (64-75)	75.4 (74-79)	78.1 (69-84)	83.1 (74-87)
1963	69.9 (66-74)	69.6 (67-72)	68.5 (62-73)	67.1 (63-71)	72.1 (66-78)	69.6 (63-79)	74.4 (66-79)	79.3 (74-82)	80.4 (78-88)	81.7 (75-87)
1964	70.7 (64-74)	71.0 (65-74)	71.0 (64-75)	71.1 (65-74)	72.3 (67-76)	71.3 (65-78)	70.9 (66-76)	71.7 (65-78)	77.9 (70-80)	82.7 (79-85)
1965	66.5 (60-71)	65.8 (60-70)	68.7 (64-74)	70.9 (64-79)	71.6 (64-77)	69.4 (63-75)	70.9 (66-76)	72.2 (68-76)	72.9 (68-79)	79.9 (72-87)
1966	70.6 (67-74)	69.7 (60-74)	69.1 (63-72)	70.2 (63-74)	72.1 (67-75)	70.8 (65-74)	73.5 (67-78)	74.9 (72-78)	76.0 (72-78)	84.7 (81-87)
1967	72.0 (67-76)	70.9 (63-76)	67.9 (64-74)	70.5 (65-77)	71.4 (64-78)	68.1 (59-75)	75.0 (72-80)	75.5 (69-88)	79.1 (75-83)	81.8 (77-88)
1968	69.5 (64-75)	68.9 (65-70)	68.1 (61-70)	65.4 (61-70)	73.9 (67-78)	68.9 (60-77)	72.9 (68-79)	75.2 (67-80)	78.6 (72-85)	85.4 (76-91)

Table 3.--Average semi-monthly maximum air temperatures and their range (in parentheses) at Eue Atoll, 1961-68 (Woodward 1972).

Table 43. (continued)

	July		August		September		October		November		December	
1961	86.5 (80-89)	88.9 (87-91)	86.8 (82-93)	89.0 (84-92)	87.0 (82-91)	86.5 (76-90)	82.4 (75-89)	79.2 (70-85)	78.4 (75-84)	78.6 (76-82)	74.9 (67-81)	73.8 (69-77)
1962	83.6 (76-86)	84.9 (78-89)	87.6 (83-92)	86.7 (80-93)	86.9 (84-90)	88.7 (84-92)	85.9 (77-89)	80.1 (72-86)	79.3 (74-85)	79.3 (75-87)	73.5 (67-79)	69.8 (64-73)
1963	82.7 (76-86)	83.3 (76-86)	83.9 (76-87)	87.1 (80-90)	85.9 (84-89)	86.2 (78-90)	82.3 (74-86)	81.8 (77-85)	79.2 (74-84)	75.3 (69-78)	70.4 (62-76)	70.9 (65-78)
1964	83.5 (79-85)	82.5 (79-84)	82.6 (79-86)	85.2 (78-88)	85.1 (82-87)	83.1 (80-87)	84.8 (83-88)	80.2 (76-83)	76.9 (72-80)	73.5 (69-80)	72.4 (67-78)	65.6 (59-70)
1965	85.7 (85-87)	84.1 (75-89)	86.6 (84-88)	86.1 (84-89)	85.3 (78-99)	81.5 (77-86)	80.5 (73-85)	79.8 (72-83)	76.5 (70-81)	76.5 (70-81)	72.2 (66-78)	66.7 (62-75)
1966	86.1 (80-89)	86.1 (79-90)	86.3 (80-89)	87.1 (80-91)	84.1 (76-89)	84.3 (80-89)	81.0 (73-84)	80.3 (75-86)	75.0 (68-80)	74.1 (70-80)	71.2 (68-74)	72.6 (69-75)
1967	82.9 (77-89)	83.7 (79-88)	84.3 (80-87)	85.8 (81-89)	86.7 (83-90)	85.0 (80-89)	83.6 (80-86)	84.1 (76-88)	81.2 (75-86)	78.2 (75-86)	73.6 (65-80)	70.1 (63-74)
1968	91.3 (87-93)	90.9 (89-93)	91.1 (87-96)	86.1 (80-93)	90.6 (87-94)	84.7 (75-93)	81.6 (76-91)	84.6 (82-95)	78.6 (68-87)	73.7 (67-81)	73.0 (68-76)	69.1 (64-73)

Woodward 1972

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	January	February	March	April	May	June
1961	-	-	-	56.9 (52-67)	61.7 (58-65)	72.3 (67-76)
1962	62.4 (56-68)	60.2 (57-65)	61.9 (57-67)	62.0 (52-66)	66.9 (63-70)	72.8 (70-75)
1963	64.7 (60-69)	63.4 (60-67)	60.8 (57-65)	63.5 (59-67)	63.9 (61-66)	67.2 (64-71)
1964	62.4 (57-68)	65.1 (61-69)	62.2 (55-70)	62.3 (56-68)	69.1 (67-72)	73.5 (72-77)
1965	60.7 (56-66)	58.3 (39-64)	63.1 (50-69)	64.1 (60-68)	61.1 (59-66)	63.8 (52-72)
1966	62.1 (57-68)	61.9 (50-69)	62.2 (50-69)	63.1 (60-67)	65.6 (60-70)	72.1 (70-73)
1967	64.7 (59-69)	62.3 (53-68)	60.5 (55-66)	61.7 (56-67)	62.3 (58-64)	71.6 (67-74)
1968	59.7 (48-66)	58.8 (50-63)	60.7 (59-65)	62.3 (55-68)	64.7 (62-68)	68.6 (62-73)
			58.7 (54-64)	59.9 (55-64)	66.7 (64-69)	73.5 (69-77)
			59.8 (53-66)	62.6 (57-66)	67.2 (64-73)	70.6 (65-75)
			57.5 (51-64)	64.3 (59-69)	70.7 (65-75)	73.1 (65-78)
			61.1 (57-65)	64.9 (60-69)	69.1 (63-74)	73.1 (65-78)

Table 4.--Average semi-monthly minimum air temperatures and their range (in parentheses) at Kure Atoll, 1961-69 (Woodward 1972).

Table Q-4. (continued)

	July		August		September		October		November		December	
1961	73.9 (68-76)	75.2 (73-76)	75.1 (74-77)	75.3 (72-78)	71.1 (72-79)	74.7 (72-77)	73.3 (64-76)	70.7 (62-74)	68.3 (64-73)	71.1 (67-74)	67.1 (57-70)	65.6 (58-71)
1962	74.7 (70-77)	73.9 (69-76)	75.5 (74-77)	74.5 (70-77)	75.5 (70-78)	75.0 (72-78)	75.3 (72-78)	70.8 (66-74)	69.7 (65-73)	69.8 (66-73)	66.3 (59-72)	63.0 (57-68)
1963	74.5 (68-77)	73.8 (71-76)	73.9 (70-77)	74.8 (69-78)	75.9 (72-78)	76.3 (72-79)	75.0 (70-79)	73.8 (70-78)	72.7 (65-77)	65.9 (56-73)	64.5 (57-72)	64.4 (54-72)
1964	72.5 (71-74)	71.1 (60-74)	71.5 (61-82)	73.0 (70-75)	73.1 (70-76)	71.9 (68-76)	70.6 (60-74)	69.8 (64-73)	68.2 (65-71)	64.1 (60-70)	62.0 (56-69)	57.6 (53-63)
1965	73.5 (71-75)	73.8 (71-75)	75.2 (74-77)	74.1 (71-77)	74.3 (70-77)	70.3 (67-74)	70.9 (67-94)	68.8 (62-72)	67.7 (65-71)	67.1 (60-70)	61.3 (54-68)	56.5 (52-62)
1966	75.6 (73-79)	76.3 (74-78)	75.2 (73-77)	75.4 (74-78)	74.1 (68-79)	72.7 (69-76)	72.5 (66-75)	69.9 (64-77)	65.9 (63-69)	66.7 (61-71)	63.1 (59-69)	65.3 (60-70)
1967	71.9 (67-75)	73.2 (69-75)	74.7 (72-78)	75.0 (73-76)	76.3 (75-78)	72.9 (68-77)	71.7 (68-75)	71.4 (68-75)	71.4 (66-75)	69.5 (62-74)	63.3 (52-72)	62.9 (55-68)
1968	74.8 (69-78)	74.6 (70-77)	77.3 (76-78)	76.4 (71-80)	76.4 (75-80)	74.4 (70-78)	72.3 (67-75)	72.1 (67-75)	66.3 (55-73)	65.5 (51-70)	67.9 (65-70)	61.3 (54-66)

Woodward 1972

Table 5.---Average semi-monthly wind speed and their range (in parentheses)

in Beaufort Scale^{1/} at Kure Atoll, 1961-68 (Woodward 1972).

	January	February	March	April	May	June		
1961	-	-	-	2.8 (0-6)	2.2 (1-4)	2.6 (0-5)	2.1 (0-3)	2.8 (1-4)
1962	3.5 (0-7)	3.1 (0-7)	2.5 (0-6)	2.7 (1-5)	3.3 (0-6)	3.3 (0-8)	3.4 (0-5)	1.6 (0-4)
1963	3.6 (1-6)	3.6 (0-7)	4.0 (1-6)	3.2 (0-5)	2.3 (0-4)	3.5 (1-6)	2.7 (1-4)	2.6 (0-4)
1964	2.5 (0-5)	2.4 (0-5)	2.6 (0-5)	2.8 (0-7)	2.8 (0-6)	3.7 (0-6)	1.9 (0-4)	2.0 (1-4)
1965	3.2 (0-6)	2.7 (0-5)	2.3 (0-4)	3.6 (1-5)	3.2 (0-6)	3.1 (0-7)	2.6 (1-5)	2.1 (0-5)
1966	1.6 (0-5)	2.6 (0-7)	2.1 (0-5)	3.4 (0-7)	2.2 (0-5)	2.2 (0-4)	1.4 (0-5)	1.6 (0-6)
1967	1.9 (1-3)	1.9 (1-3)	2.3 (0-4)	1.6 (0-3)	2.3 (0-4)	1.9 (1-4)	2.0 (0-3)	2.5 (0-3)
1968	2.4 (0-4)	3.1 (1-5)	3.5 (1-6)	4.0 (2-7)	2.8 (1-5)	2.7 (1-5)	2.9 (1-5)	1.6 (1-4)

^{1/} *Beaufort Scale: 0 = 1 knot, 1 = 1-3 knots, 2 = 4-7 knots, 3 = 8-12 knots, 4 = 13-18 knots, 5 = 19-24 knots, 6 = 25-31 knots, 7 = 32-38 knots, 8 = 39-46 knots

Woodward 1972

Table G-2. (continued)

	July		August		September		October		November		December	
1961	1.8 (0-3)	2.6 (0-6)	2.6 (0-5)	2.0 (0-5)	2.3 (0-5)	2.4 (0-5)	2.6 (1-5)	3.6 (1-6)	2.4 (0-5)	2.9 (1-5)	2.9 (0-6)	3.7 (0-5)
1962	3.0 (1-7)	2.6 (0-6)	2.8 (1-5)	1.6 (0-5)	2.1 (0-4)	2.3 (0-8)	2.9 (1-5)	3.0 (0-5)	2.2 (0-5)	3.0 (1-5)	3.6 (0-7)	2.6 (0-5)
1963	2.7 (1-4)	3.4 (1-5)	3.3 (1-8)	1.9 (0-6)	2.0 (0-6)	3.0 (1-7)	2.7 (1-6)	3.5 (1-6)	2.8 (0-6)	3.0 (0-7)	3.1 (0-6)	3.2 (0-6)
1964	2.9 (1-6)	2.8 (1-6)	3.0 (1-5)	2.1 (0-4)	2.5 (1-6)	2.3 (0-5)	2.0 (0-4)	3.2 (2-7)	3.1 (1-5)	2.9 (1-6)	2.7 (0-4)	4.0 (0-9)
1965	2.2 (0-4)	3.1 (1-6)	2.7 (1-4)	2.1 (0-4)	2.2 (0-4)	2.9 (0-6)	1.8 (0-5)	2.2 (0-5)	2.6 (0-4)	3.0 (0-5)	2.0 (0-8)	2.2 (0-5)
1966	1.9 (0-6)	2.4 (1-5)	2.8 (0-5)	2.3 (1-5)	2.3 (0-5)	2.0 (0-8)	3.0 (1-6)	2.1 (0-4)	2.3 (0-5)	2.2 (0-4)	2.2 (0-8)	2.0 (1-4)
1967	1.8 (0-3)	2.0 (0-3)	2.1 (0-3)	2.2 (1-3)	2.2 (0-3)	1.7 (0-4)	1.5 (0-3)	1.6 (0-3)	2.1 (1-5)	2.3 (1-4)	2.5 (0-5)	2.5 (0-5)
1968	2.5 (1-3)	2.7 (1-4)	2.4 (0-3)	2.3 (0-5)	2.2 (0-4)	2.3 (0-5)	3.1 (1-5)	2.2 (0-4)	2.6 (1-5)	2.9 (1-5)	3.6 (1-6)	3.0 (1-7)

Table 6.--Semi-monthly rainfall (in) at Midway Atoll, 1963-68

(Woodward 1972).

	January		February		March		April		May		June	
1963	3.2	3.5	1.5	1.7	3.9	9.3	2.8	0.5	1.4	0.1	0.1	1.4
1964	1.2	3.5	1.8	0.5	6.8	2.4	1.9	0.2	3.0	0.1	1.3	0.9
1965	1.3	1.2	2.0	1.5	2.0	1.1	0.1	2.1	0.2	0.1	1.8	3.7
1966	0.8	1.6	0.5	0.4	1.1	0.6	0.8	0.1	1.3	1.2	0.1	0.7
1967	0.7	2.2	3.1	5.0	1.7	0.5	0.5	1.8	0.7	0.4	3.0	0.1
1968	2.7	3.6	3.9	0.6	0.1	0.1	1.0	0.1	0.7	1.8	1.7	0.8
	July		August		September		October		November		December	
1963	1.3	5.3	2.7	0.3	0.4	2.7	3.8	2.4	9.2	1.7	1.6	0.4
1964	0.7	1.9	0.8	0.4	0.3	0.8	1.4	4.7	7.0	2.1	1.7	3.9
1965	0.3	1.0	0.2	1.3	1.3	2.2	0.2	0.6	0.8	3.2	0.5	3.4
1966	0.3	1.9	0.8	0.9	4.4	0.1	7.4	1.3	1.4	1.3	0.9	0.5
1967	5.9	7.4	6.5	0.3	0.9	1.0	1.3	0.3	7.0	3.3	2.8	2.0
1968	0.3	1.6	0.5	6.7	3.1	2.3	0.9	0.5	1.1	2.8	6.0	11.9

Locality	Period	Number of days		Yellowfin		Skipjack		Mixed ^{1/}		Unidentified		Total fish schools		Bird flocks	
		Fishing and scouting	Running	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day
Hawaiian Is.	Mar.-May	0	9	0	0.0	7	0.8	0	0.0	7	0.8	14	1.6	18	2.0
	June-Aug.	33	15	4	0.1	81	1.7	0	0.0	20	0.4	105	2.2	100	2.1
	Sept.-Nov.	4	31	0	0.0	17	0.5	0	0.0	21	0.6	38	1.1	47	1.3
	Dec.-Feb.	0	4	1	0.2	1	0.2	0	0.0	1	0.2	3	0.8	3	0.8
Leeward Is.	Mar.-May	1	4	1	0.2	3	0.6	0	0.0	25	5.0	29	5.8	47	9.4

Table 7a.--Summary of island observations on fish schools and bird

flocks (Murphy and Ikehara 1955).

^{1/} Yellowfin and skipjack.

Locality	Period	Number of days		Yellowfin		Skipjack		Unidentified		Total fish schools		Bird flocks		Number of birds	
		Fishing and scouting	Running	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day	Num-ber per day
Hawaiian Is.	Mar.-May	0	10	0	0.0	3	0.3	5	0.5	8	0.8	12	1.2	558	55.8
	June-Aug.	1	8	0	0.0	4	0.4	10	1.1	14	1.6	19	2.1	1212	134.7
	Sept.-Nov.	0	16	0	0.0	10	0.6	7	0.4	17	1.1	16	1.0	1283	80.2
	Dec.-Feb.	0	7	0	0.0	1	0.1	1	0.1	2	0.3	3	0.4	144	20.6
Leeward Is.	Mar.-May	0	2	0	0.0	2	1.0	1	0.5	3	1.5	3	1.5	85	42.5

Table 7b.--Summary of semioceanic ^{1/} observations associated with

particular island groups (Murphy and Ikehara 1955).

^{1/} Semi-oceanic observations were considered to be from 60 to 180 miles from the islands.

^{2/} Includes scattered birds.

Murphy and Ikehara 1955
Table 7a

-+HANDLINE CATCH (KG)

NECKER

1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
-	-	-	-	-	-	38	-	-	-
28	93	742	-	80	1,035	836	373	723	944
15	117	79	-	3	40	80	146	208	-
-	-	-	-	-	-	-	-	-	-
51	269	-	11	93	234	155	334	235	109
-	944	357	180	300	298	2,107	1,905	347	20
8,239	6,461	4,467	1,319	12,166	13,846	7,742	16,526	7,362	9,435
3,834	992	1,375	613	5,809	2,011	2,102	3,548	968	1,726
8	18	12	9	347	171	371	623	262	55
-	-	-	-	-	-	-	-	-	-
2,126	1,449	412	394	1,441	2,702	337	560	1,601	6,208
122	40	84	18	831	106	1,747	995	1,363	103
111	200	409	54	1,508	1,846	4,095	2,524	2,141	557
1,763	1	11	-	135	308	491	1,268	649	21
5,680	5,609	8,317	15,649	10,993	10,087	1,094	947	3,958	7,805
3	-	-	-	7	4	10	5	21	19
6	-	-	-	10	-	6	-	-	-
2	-	-	-	-	-	-	-	-	-
16	-	6	-	-	-	-	-	-	-
-	-	-	-	-	-	10	-	5	-
-	24	-	91	18	36	-	-	-	-
-	54	-	-	-	-	-	-	-	-
1	-	-	-	-	1	-	-	-	-
6	10	-	-	14	42	9	7	-	-
-	-	-	-	-	-	-	-	106	-
-	-	-	-	-	14	9	-	-	-
3	22	53	20	375	502	261	426	10.6	3
4	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	1	-	-	-
-	-	-	-	-	-	-	11	-	-
-	-	2	-	14	7	7	-	4	210

TROLL CATCH (KG)

-NIHOA

NECKER

[illegible]

22,018	16,303	16,326	18,358	34,197	33,290	21,508	30,198	20,059	27,212	182	1,067	7,177	1,350
\$18,342	\$14,809	\$14,983	\$15,007	\$39,541	\$48,220	\$43,009	\$64,627	\$43,948	\$62,974	\$120	\$970	\$4,589	\$955

Month	Total hours trolled	Average number of lines fished	SJ	YF	KK	AL	SD
January	30.3	3.25	2	0	0	2	0
February	47.5	4.50	6	3	0	2	1
March	4.1	6.00	0	0	0	4	0
April	190.1	3.06	2	1	10	3	0
May	182.3	4.19	6	14	14	3	0
June	104.9	4.18	1	3	9	0	0
July	239.9	2.77	7	9	19	0	0
August	65.0	4.83	10	11	0	0	0
September	24.0	8.00	0	0	0	0	0
October	39.2	2.00	0	1	5	0	0
November	74.3	2.71	5	1	0	0	0
December	21.3	5.50	0	0	6	0	0

Table --

Table 9.--Catches and catch rates of tunas and tuna-like fishes by trolling gear during exploratory surveys of research vessels operating in and around NWHI waters, 1954-64. SJ - Skipjack; YF - Yellowfin; KK - Kawaikawa; AL - Albacore; SD - Sarda sp.; BE - Bigeye; MA - Mahimahi; and WA - Wahoo.

BE	Total tuna	MA	WA	Others	Catch/line-hour	
					Tuna	MA
0	4	1	0	0	0.041	0.010
0	12	0	0	0	0.056	0.000
0	4	1	0	0	0.163	0.007
0	16	23	1	1	0.028	0.040
0	37	24	2	1	0.048	0.031
0	13	24	0	0	0.030	0.055
1	36	32	4	0	0.054	0.048
0	21	14	0	0	0.067	0.044
0	0	3	0	0	0.000	0.016
0	6	2	0	0	0.076	0.026
0	6	7	2	2	0.030	0.035
0	6	3	1	0	0.051	0.026

Table 10.--Percentages of the North Pacific longline fishing effort and catches, by species, of Japanese vessels made in the NWHI region, 1964-73.

RMS
11/14/74

YR	NORTH PACIFIC OCEAN (NPO)		C/O	BLUEFIN			ALBACORE			BIGEYE			YELLOWFIN		
	HOOKS ^{10³}	NWHI REGION HOOKS ^{10³}		NPO NO. ^{10³}	NWHI NO.	%	NPO NO. ^{10³}	NWHI NO.	%	NPO NO. ^{10³}	NWHI NO.	%	NPO NO. ^{10³}	NWHI NO.	%
64	139,893	3,759	2.7	20 ³¹	37	0.2	927	3,105	0.3	857	15,222	1.8	517	8,730	1.7
65	152,942	3,079	2.0	16 ³¹	19	0.1	801	1,846	0.2	713	7,443	1.0	646	6,815	1.0
66	149,691	937	0.6	8	0	0.0	1,491	1,780	0.1	979	4,927	0.5	586	1,453	0.2
67	192,960	1,696	0.8	6	0	0.0	1,741	3,826	0.2	797	6,313	0.8	529	2,975	0.6
68	165,372	3,639	2.2	4	1	0.0	1,360	10,370	1.0	736	13,399	1.8	428	5,348	1.2
69	168,750	2,259	1.3	3	6	0.2	1,017	12,386	1.2	915	22,026	2.9	598	3,418	0.6
70	162,674	5,449	3.3	2	5	0.2	786	13,252	1.7	806	22,709	3.6	837	19,609	2.3
71	139,680	3,176	2.3	2	5	0.2	528	12,187	2.3	701	18,357	2.7	402	11,259	2.8
72	124,571	3,378	2.7	1	2	0.2	559	10,667	3.3	827	29,522	3.6	411	5,994	1.4
73	134,997	3,211	2.4	1	8	0.8	667	23,206	3.6	745	21,991	3.6	454	4,246	0.9
Σ	1,531,530	30,583	$\bar{x}$ 2.0						1.4						

Data for hooks fished in the North Pacific are from Japan Fisheries Agency (1973).
 Data for 1964-73 are from Japan Fisheries Agency, 1967a, 1967b, 1968, 1969, 1970, 1971, 1972, 1973, 1974a, and 1974b.
 INCLUDE SOUTHERN BLUEFIN

BROADBILL			STRIPED MARLIN			BLUE MARLIN			BLACK MARLIN			SALEFISH & SHORTBILL			SKIATACK		
NPO	NWHI	%	NPO	NWHI	%	NPO	NWHI	%	NPO	NWHI	%	NPO	NWHI	%	NPO	NWHI	%
NO. ^{10³}	NO.		NO. ^{10³}	NO.		NO. ^{10³}	NO.		NO. ^{10³}	NO.		NO. ^{10³}	NO.		NO. ^{10³}	NO.	
111	1,581	1.4	210	27,159	12.9	105	3,368	3.2	6	320	5.3	35	2,902	8.3	13	276	2.1
147	744	0.5	156	37,309	23.9	83	3,760	4.5	12	102	0.8	41	2,260	5.5	30	1,920	6.4
172	287	0.2	98	5,426	5.5	74	506	0.7	7	42	0.6	35	256	0.7	23	979	4.2
194	618	0.3	159	17,819	11.2	79	1,255	1.6	6	23	0.4	41	710	1.7	23	377	1.6
158	2,471	1.6	154	27,551	17.9	62	1,898	3.1	3	42	1.4	33	2,568	7.8	20	675	3.3
148	1,083	2.2	101	5,716	5.6	72	302	0.4	5	12	0.2	23	238	1.0	22	278	1.3
108	1,418	1.3	242	37,942	15.7	122	5,536	4.5	4	66	1.6	41	4,816	11.7	47	865	1.8
107	705	0.6	130	9,693	7.4	59	935	1.6	4	70	1.8	20	499	2.5	15	347	2.3
92	1,514	1.6	70	5,381	7.7	57	768	1.3	4	36	0.9	18	479	2.7	13	284	2.2
99	839	0.8	100	4,797	4.8	69	351	0.5	3	30	1.0	31	777	2.5	13	217	1.7

ed 1975

le 11.--Fishes, macro-invertebrates, algae and bottom substrates sampled (S) and observed (O) during surveys at Nihoa, Necker, French Frigate Shoals and Laysan Island (Narrative Report, Townsend Cromwell, cruise 76-04-71,

SHES: May3-June 9, 1976).

Common Name	FAMILY NAME Scientific Name	French			
		Nihoa Island	Frigate Shoals	Laysan Island	Necker Island
ARKS	CARCARHINIDAE				
ark	(Unidentified species)	S	O	S,O	O
ger shark	Galeocerdo cuvieri	-	O	S	-
YS	MYLIOBATIDAE				
himanu	Aetobatus narinari	-	O	O	-
YS	MOBULIDAE				
lalua	(Unidentified species)	O	-	-	-
ZARDFISHES	SYNODONTIDAE				
lae	Synodus variegatus	-	-	O	-
ITFISHES	DUSSUMIERIIDAE				
ha	Spratelloides delicatulus	-	O	O	-
UIRRELFISHES	HOLOCENTRIDAE				
la'ihl	Adioryx spinifer (=Holocentrus spinifer)	-	O	-	-
la'ihl	A. xantherythrus (=H. xantherythrus)	S	-	O	-
la'ihl	Flammeo sammara (=H. sammara)	-	O	-	-
'u	Myripristis amaenus (=M. argyromus)	-	-	O	-
RRACUDAS	SPHYRAENIDAE				
walea	Sphyræna helleri	S	-	-	-
EDLEFISHES	BELONIDAE				
ha'aha	Strongylura gigantea	S, O	S, O	-	O
LFBEAKS	HEMIRAMPHIDAE				
eihe	(Unidentified species)	-	O	-	-

Table 12.--Ten species of fish observed during underwater fish counting transects, ranked by estimated densities and number of individuals counted (Narrative Report, Townsend Cromwell, cruise 76-04-71, May 3-June 9, 1976).

Estimated Densities:

Rank	Common Name	Scientific Name	Density Pounds/ Acre	Occurrence (No. of Stations)
	Weke-'a'a	Mulloidichthys samoensis	1,969	3
	Uhu uliuli	Scarus perspicillatus	1,948	3
	White ulua	Carangoides ajax	1,022	1
	Nenu	Kyphosus cinerascens	559	4
	Kala	Naso unicornis	384	4
	Manini	Acanthurus triostegus (=A. sandvicensis)	375	4
	Hinalea	Thalassoma purpurum (=T. fuscum and T. umbrostigma)	152	3
	'Omilu	Caranx melampygus	128	3
	Hinalea luahine	Thalassoma ballieui	85	4
	White banded maiko	Acanthurus leucopareus	81	4

Number of Individuals:

Rank	Common Name	Scientific Name	Density Pounds/ Acre	Occurrence (No. of Stations)
	Piha	Spratelloides delicatulus	50,000	2
	Weke-'a'a	Mulloidichthys samoensis	1,006	3
	Manini	Acanthurus triostegus (=A. sandvicensis)	239	4
	Nenu	Kyphosus cinerascens	222	4
	Uhu uliuli	Scarus perspicillatus	180	3
	Kole	Ctenochaetus strigosus	108	4
	Hinalea lau-wili	Thalassoma duperreyi	105	3
	Blue damselfish	Chromis ovalis	100	1
	Kala	Naso unicornis	98	4
	'Omaka	Stethojulis balteata (=S. axillaris and S. albobittata)	75	2

ACRO-INVERTEBRATES:

Common Name	FAMILY NAME Scientific Name	French			
		Nihoa Island	Frigate Shoals	Laysan Island	Necker Island
PINY LOBSTER la	PANULIURIDAE Panalirus marginatus (=p. Japonicus)	-	0	-	-
COCK CRAB A'ama	GRAPSIDAE Grapsus grapsus	0	-	0	S, 0
HOST CRAB O-hi-ki	OCYPODIDAE Ocypode ceratophthalma	-	0	0	-
QUILLA Alo'alo	SQUILLIDAE Squilla oratoria	0	0	-	-
RINE SHRIMP rine shrimp	--- Artemia sp.	-	-	0	-
ARNACLES arnicle	BALANIDAE Balanus sp.	-	-	0	-
OOSE NECK BARNACLES oose neck barnicle	LEPADIDAE Lepas sp.	-	0	0	-
OWRY owry	CYPRANIDAE Cypraea spp.	-	-	-	S
EA SNAILS ipihi	NERITIDAE Nerita spp.	S, 0	-	0	S, 0
IMPETS pihi	PATELLIDAE Patella spp.	S, 0	-	-	S, 0
COCK SHELLS cock shell	MURICIDAE Purpura spp.	S, 0	-	-	S, 0
ERIWINKLES eriwinkle	LITTORINIDAE Littorina spp.	0	-	0	0
URBINE SHELL at-eye shell	TURBINIDAE Turbo intercostalis	-	-	0	0

Common Name	FAMILY NAME Scientific Name	French					Neckor Island
		Nihoa Island	Frigate Shoals	Laysan Island			
MOORISH IDOLS ihikihi	ZANCLIDAE Zanclus canescens	0	0	0		0	
MURGEONFISHES anini urf maiko aikoiko aiko alani ualu ualu ole au'i-pala ala ala	ACANTHURIDAE Acanthurus triostegus (=A. sandvicensis) A. guttatus A. leucopareius A. nigroris A. dussumieri A. xanthopterus A. mata Ctenochaetus strigosus Zebrasoma flavescens Naso lituratus N. unicornis	0 0 0 0 0 0 0 0 0 0 0	0 - 0 0 - - 0 - - - 0	S, 0 - 0 S, 0 - - 0 0 0 0 0		0 - - - - - - - - -	
RIGGERFISHES umuhumu-'ele'ele umuhumu-uli umuhumu-umauma-lei umuhumu-mimi	BALISTIDAE Melichthys niger (=M. buniwa) M. vidua (=M. nycteris) Sufflamen bursa (=Balistes bursa) S. frenatus (=Balistes capistratus)	S, 0 S, 0 0 S	0 - - -	- - - -		- - - -	
HARPBACKED PUFFERS potted puffer	CANTHIGASTERIDAE Canthigaster jactator	-	0	0		-	
LENNIES ao'o	BLENNIDAE Istiblennius zebra	0	-	0		0	0
LEOTRID leotrid	ELEOTRIDAE (Unidentified species)	-	-	-		-	0
UNA awakawa	SCOMBRIDAE Euthynnus yaito	S	-	S		-	-

Common Name	FAMILY NAME Scientific Name	French				Necker Island
		Nihoa Island	Frigate Shoals	Laysan Island		
ANGEL FISHES	POMACANTHIDAE					
Black banded angelfish	Holacanthus arcuatus	0	-	-	-	
DAMSELFISHES	POMACENTRIDAE					
Kupipi	Abudefduf sordidus	0	-	0	0	
Maomao	A. abdominalis	-	0	S, 0	-	
Damselfish	A. imparipennis	0	-	-	-	
Damselfish	Pomacentrus jenkinsi	0	0	0	-	
Blue damselfish	Chromis ovalis	0	-	-	-	
HAWKFISHES	CIRRHITIDAE					
Po'o-pa'a	Cirrhitus pinnulatus (=C. alternatus)	-	0	-	-	
WRASSES	LABRIDAE					
'A'awa	Bodianus bilunulatus	S, 0	S, 0	S	-	
Cleaner wrasse	Labroides phthirophagus	-	0	0	-	
Po'ou	Cheilinus rhodochrous	S	S	-	-	
Wrasse	Hemipteronotus taeniourus (=Novaculichthys taeniourus)	-	-	0	-	
Lae-nihi	H. umbrilatus	-	-	0	-	
Hinalea lau-wili	Thalassoma duperreyi	-	0	0	-	
Hinalea luahine	T. ballieui	S, 0	S, 0	S, 0	S, 0	
Wrasse	T. purpureum (=T. umbrostigma and T. fuscum)	S	0	S, 0	0	
Hinalea i'iwi	Gomphosus varius	-	0	0	-	
Hilu	Coris flavovittata	0	0	0	-	
'Omaka	Stethojulis balteata (=S. axillaris and S. albobittata)	-	0	0	-	
Hinalea 'aki-lolo	Macropharyngodon goeffroyi	-	0	-	-	
'Opule	Anampses cuvieri (=A. godeffroyi).	-	-	0	-	
PARROT FISHES	SCARIDAE					
Uhu	Calotomus spinidens (=C. sandvicensis)	-	0	-	-	
Uhu	Scarus dubius	0	0	-	-	
Uhu uliuli	S. perspicillatus	-	0	S, 0	-	
Uhu	S. sordidus	-	-	0	-	

Common Name	FAMILY NAME Scientific Name	French				Neck Island
		Nihoa Island	Frigate Shoals	Laysan Island		
RED BIG EYE 'Aweoweo	PRIACANTHIDAE <i>Priacanthus cruentatus</i>	-	S, O	-	-	-
KUHLIDS Aholehole	KUHLIIDAE <i>Kuhlia sandvicensis</i>	O	S	S, O	O	O
MULLETS Uouoa 'Ama 'ama	MUGILIDAE <i>Neomyxus chaptalii</i> <i>Mugil cephalus</i>	-	S S	S	-	-
JACKS 'Opelu Akule White ulua Papa ulua 'Omilu	CARANGIDAE <i>Decapterus pinnulatus</i> <i>Trachurops crumenophthalmus</i> <i>Carangoides ajax</i> <i>C. ferdau</i> <i>Caranx melampygus</i>	- - - S, O -	S S S, O S, O S, O	- - S O S, O	- - S O S, O	- - - - S
SNAPPERS Gurutu	LUTJANIDAE <i>Aphareus furcatus</i>	S	-	-	-	-
GOATFISHES Weke 'a 'a Malu Moano kea Kumu Moano	MULLIDAE <i>Mulloidichthys samoensis</i> <i>Parupeneus pleurostigma</i> <i>P. chryserydros</i> <i>P. porphyreus</i> <i>P. multifasciatus</i>	- - - - O	S, O O - O S, O	O O O - O	- - - - -	- - - - -
RUDDERFISHES Nenu	KYPHOSIDAE <i>Kyphosus cinerascens</i>	S, O	S, O	S, O	S, O	S,
BUTTERFLYFISHES Blue striped butterflyfish Cross striped butterflyfish Tear drop butterflyfish Orange striped butterflyfish Butterflyfish	CHAETODONTIDAE <i>Chaetodon fremblii</i> <i>C. auriga</i> <i>C. unimaculatus</i> <i>C. ornatissimus</i> <i>C. miliaris</i>	- - - O -	O O - - O	O - O - O	- - - - -	- - - - -

Table 13.--Number of fish species observed, estimated densities, and

major fish species ranked by density at Nihoa Island,

French Frigate Shoals, and Laysan Island (Cruise Report,

Townsend Cromwell, cruise 76-04-71, May 3-June 9, 1976).

Location	No. of fish species	Estimated densities (lb/acre)	Major fish species ranked in terms of greatest densities
Nihoa Island	26	147.61	1. <u>Chromas ovalis</u> 2. <u>Ctenochaetus strigosus</u> 3. <u>Naso lituratus</u>
French Frigate Shoals			
East Island	29	1,979.89	1. <u>Scarus perspicillatus</u> 2. <u>Kyphosus cinerascens</u> 3. <u>Mulloidichthys samoensis</u>
Whale-Skate Island	32	4,232.31	1. <u>Mulloidichthys samoensis</u> 2. <u>Carangoides ajax</u> 3. <u>Scarus perspicillatus</u>
Laysan Island	34	756.95	1. <u>Scarus perspicillatus</u> 2. <u>Acanthurus triostegus</u> (= <u>A. sandvicensis</u>) 3. <u>Thalassoma purpuraceum</u> (= <u>T. umbrostigma</u> and <u>T. fuscum</u>)

Species	Location	Depth (m)	Trawl No.	No. measured	Size range (mm)	Average length (mm)	Average weight (gm)
種 名	調査海山	水深 (m)	網次番号	測定尾数	標本体長 (FL・mm)	平均体長 (mm)	平均体重 (g)
キンメダイ	カ ン ム	355	T 2	40	124 - 281	199	189
"	Kanmu	350	T 3	12	179 - 228	191	151
"	"	335	T10	40	156 - 305	230	310
"	"	380	T11	2	249 - 298	274	547
"	"	383	T12	170	161 - 220	186	150
"	"	370	T13	40	176 - 234	203	193
"	ハンコック 南 東	265	T 6	9	232 - 336	271	428
クサカリ ツボダイ	カ ン ム	355	T 2	88	246 - 300	273	339
"	"	350	T 3	32	246 - 311	274	338
"	Kanmu	355	T 8	3	262 - 297	275	453
"	"	365	T 9	91	244 - 320	273	347
"	"	335	T10	40	252 - 302	273	348
"	"	380	T11	7	249 - 276	267	318
"	"	383	T12	87	262 - 325	289	382
"	"	370	T13	91	249 - 307	273	348
"	ハンコック 南 東	270	T 5	107	246 - 313	275	356
"	H	265	T 6	110	233 - 320	271	322
"	"	265	T 7	104	238 - 311	270	320
クサカリ ツボダイ	ハンコック 南 東	265	T 3	271	229 - 325	272	304
"	Hancock	265	T 4	124	240 - 325	272	309
"	"	265	T 8	240	240 - 310	272	323
"	"	265	T 9	154	229 - 316	268	291
"	"	265	T10	191	242 - 305	271	333
"	"	270	T11	133	244 - 310	272	332
"	"	265	T25	94	225 - 308	271	324
"	"	265	T26	119	240 - 383	277	346
"	北 西	267	T 5	210	238 - 310	274	348
"	"	290	T 7	163	210 - 313	273	336
"	"	263	T27	51	240 - 304	271	326
"	"	270	T28	2	273 - 273	273	350

Table 14.--Fishing and size information of alphoncins and armorheads taken at Kanmu and Hancock Seamounts R/V Kaiyo Maru during the North Pacific seamount surveys in 1972 (Japan Fisheries Agency 1974b).

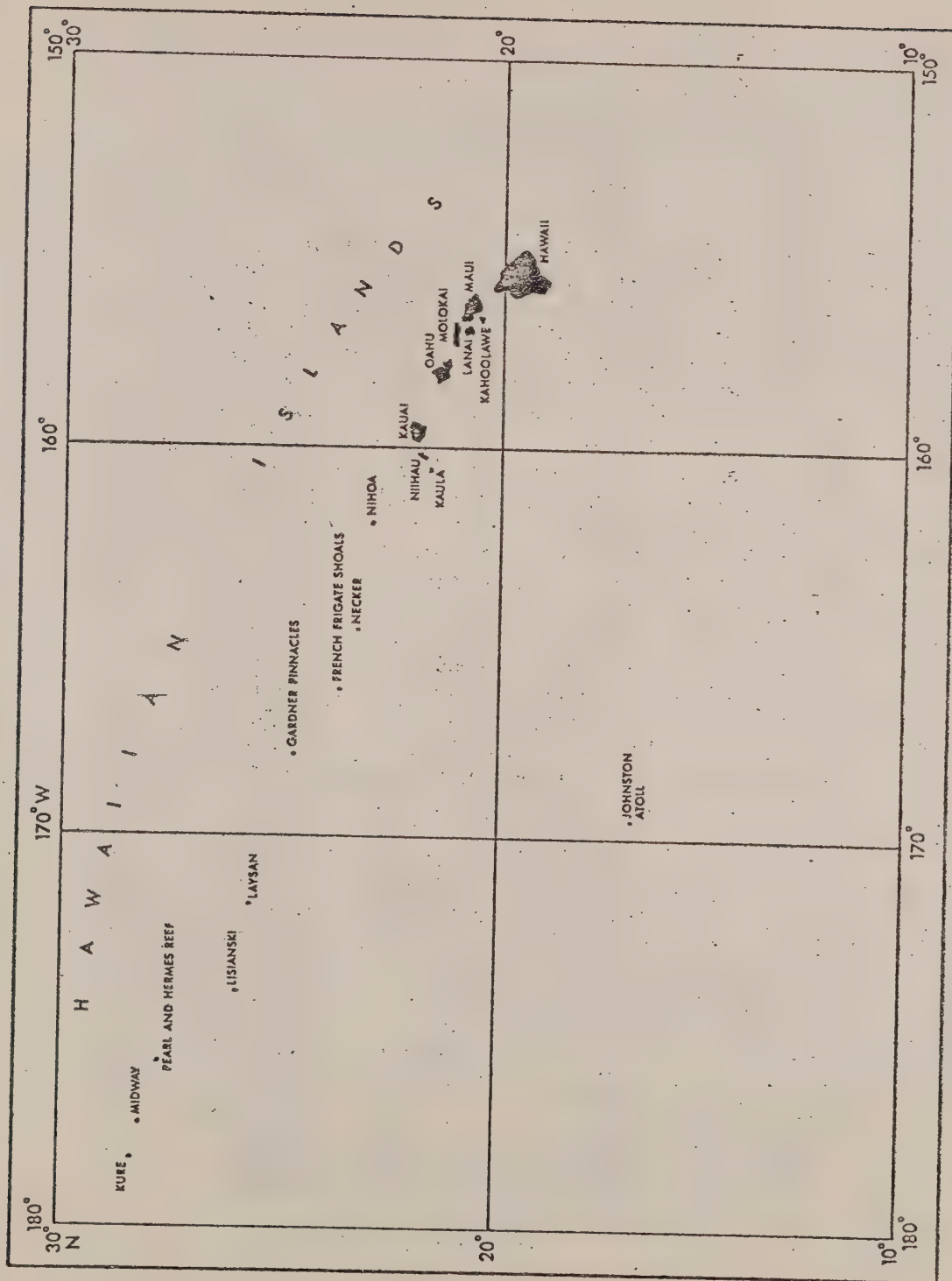


Figure 1a. The Hawaiian Islands.

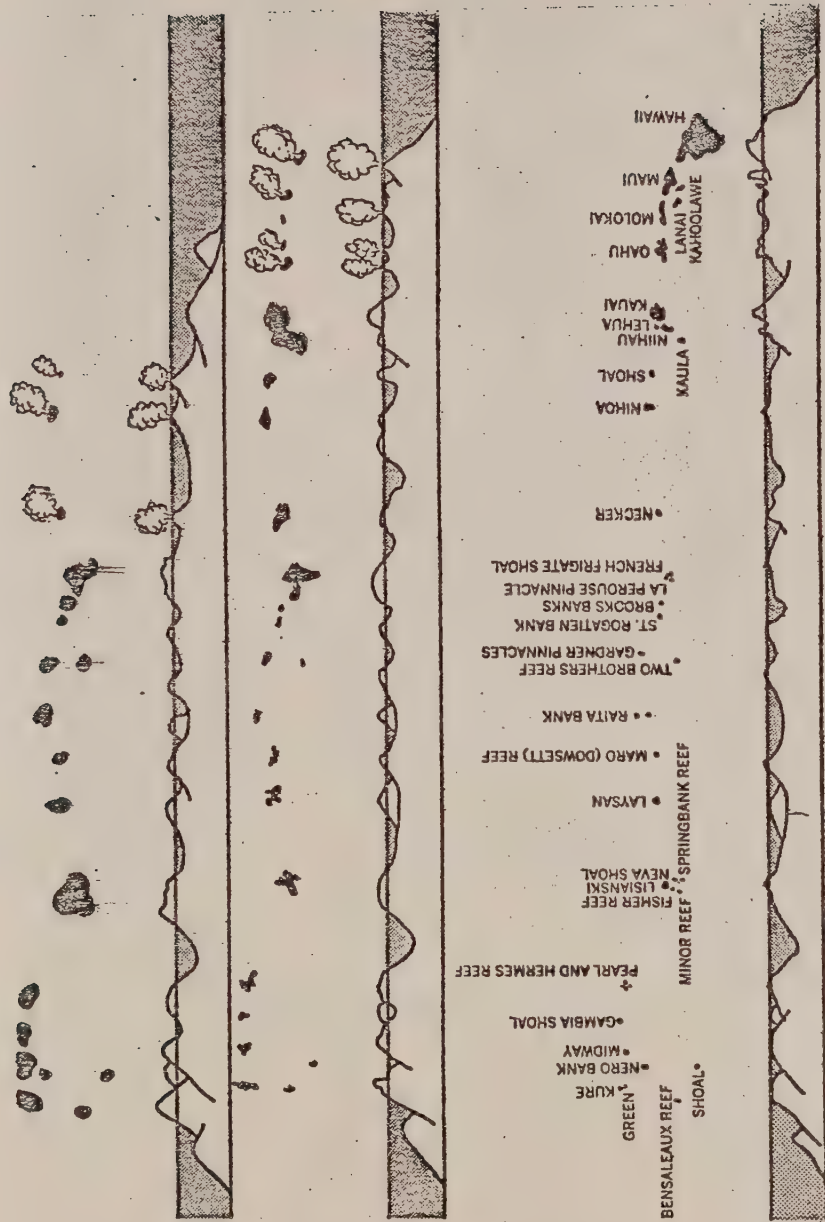


Figure 16--Three stages of island building in the Hawaiian chain. The first stage represents how the chain might have looked about ten million years ago, the second perhaps five million years ago or less, and the third is the present-day Hawaiian chain (Carlquist 1970).

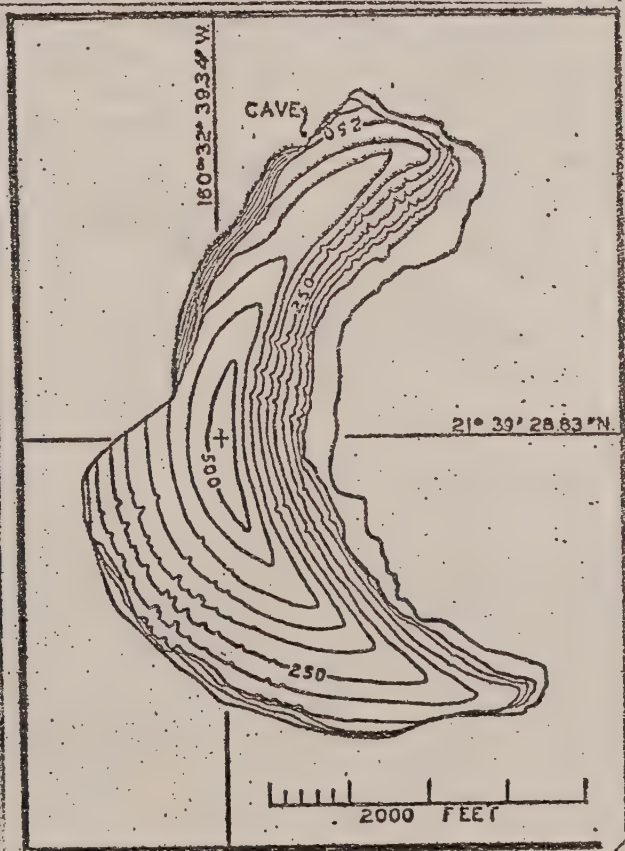


Figure 2.—Kaula Island (Bryan 1942).

Bryan 1942

Fig. 3

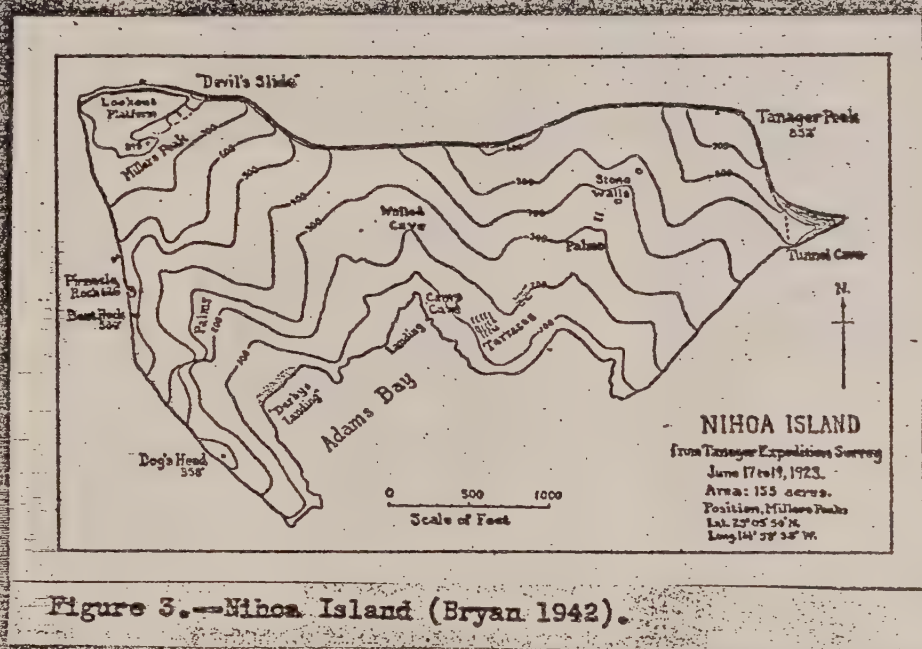


Figure 3.--Nihoa Island (Bryan 1942).

Bryan 1942

Fig 4

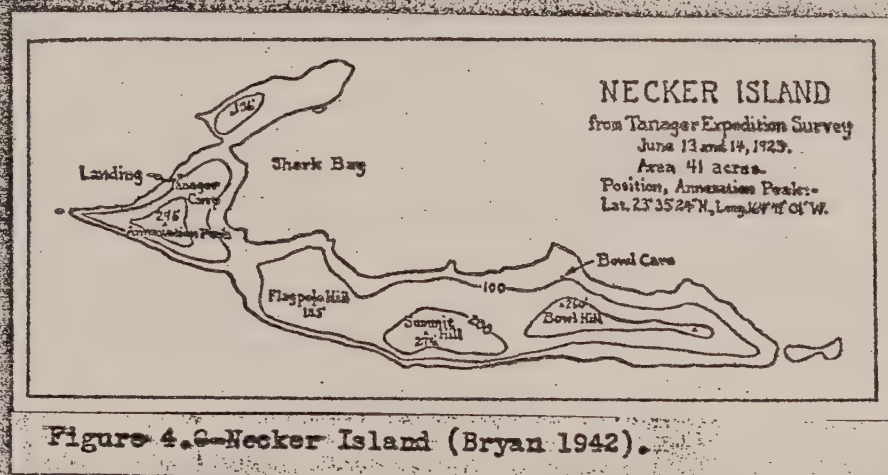
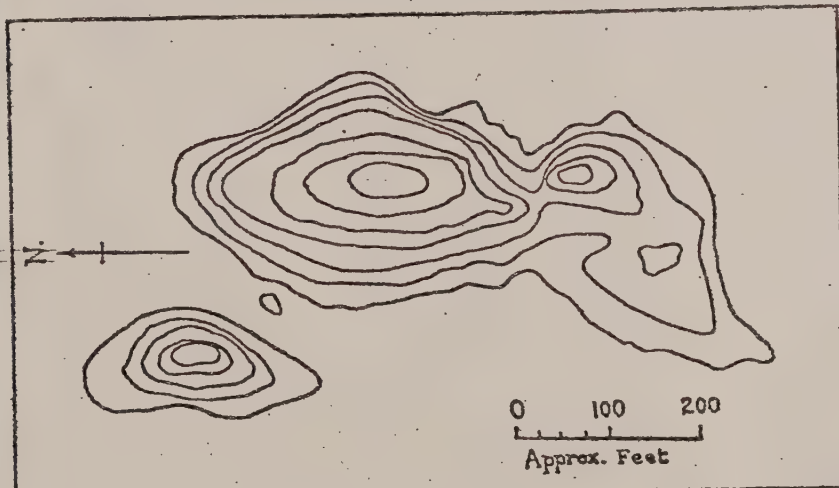




Figure 1. French Frigate Shoals (Amerson 1971).

Bryan 1942

Fig. 6



(After H. S. Palmer)

Figure 6.—Gardner Pinnacles (Bryan 1942).

Bryan 1942

Fig. 7

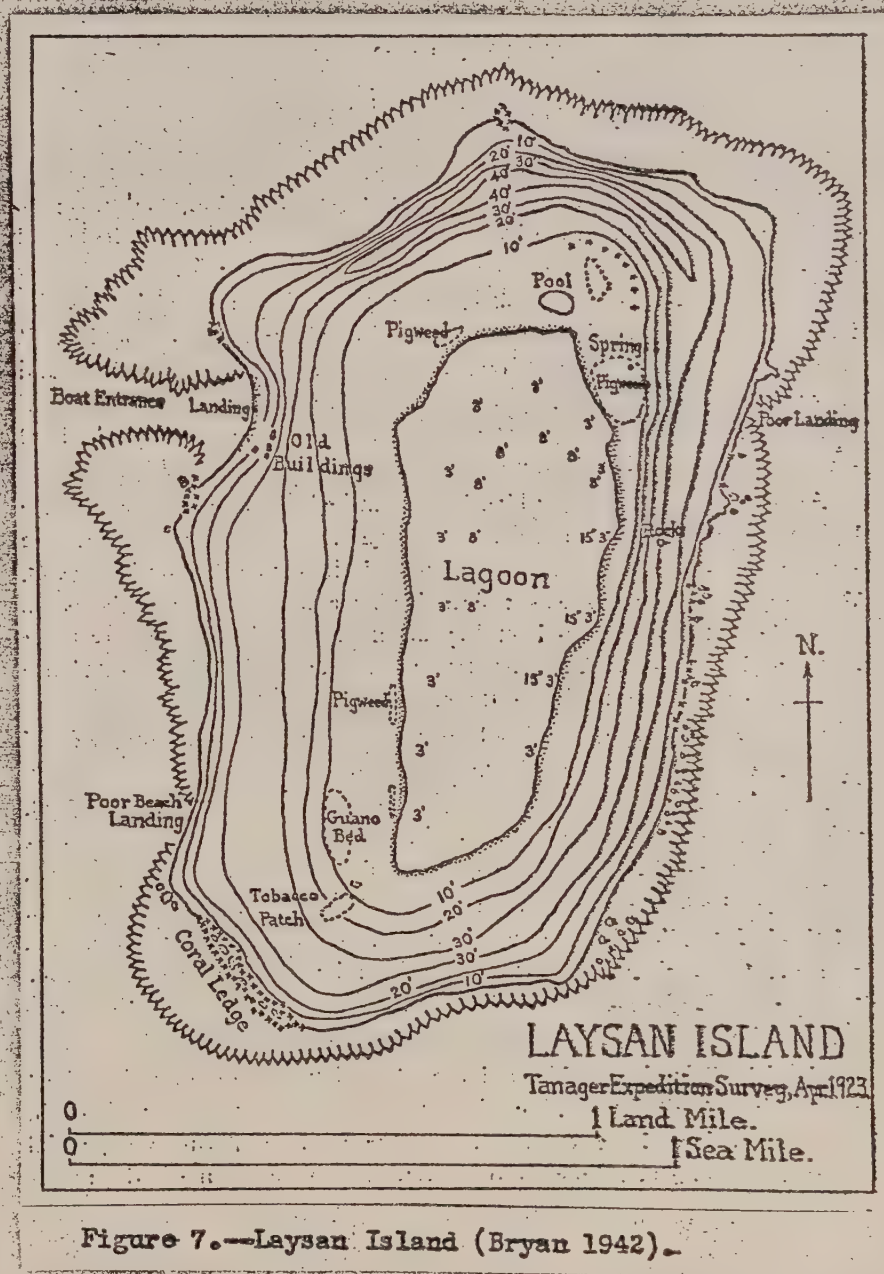


Figure 7.--Laysan Island (Bryan 1942).

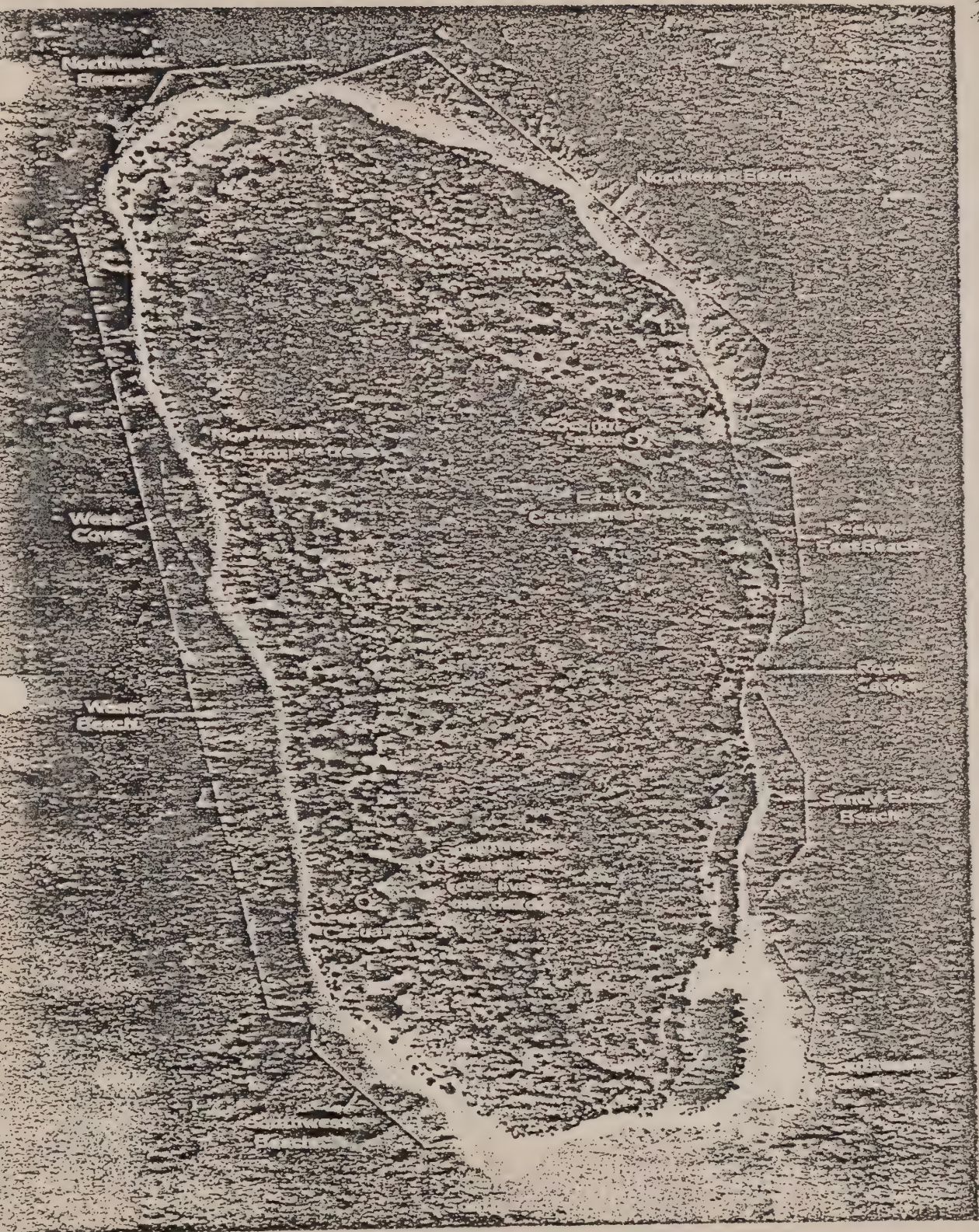


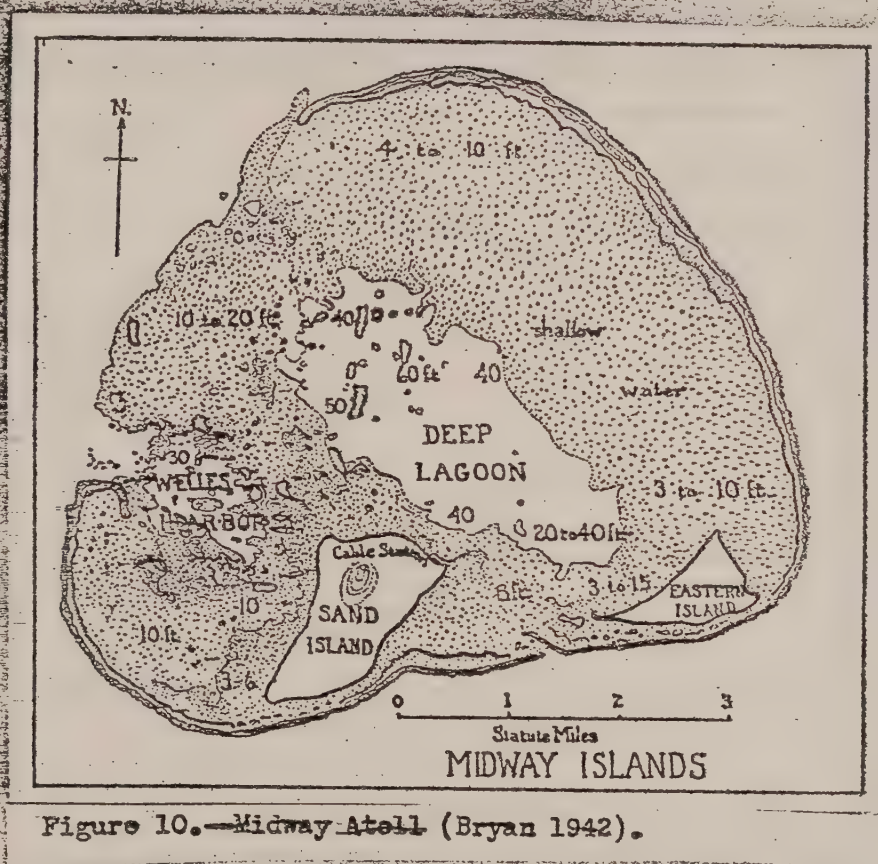
Figure 8.--Lisianski Island (Clapp and Wirtz 1975).



Figure 9.--Pearl and Hermes Reef (Amerson, Clapp and Wirtz 1974).

Bryan 1942

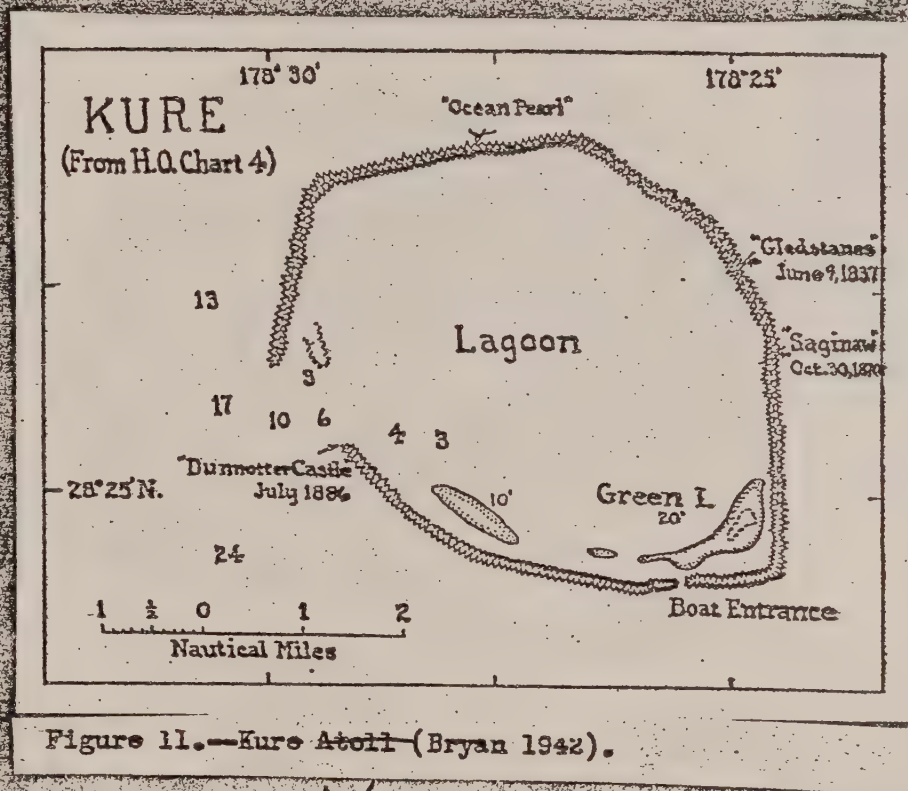
Fig. 10



Island

Bryan 1942

Fig. 11



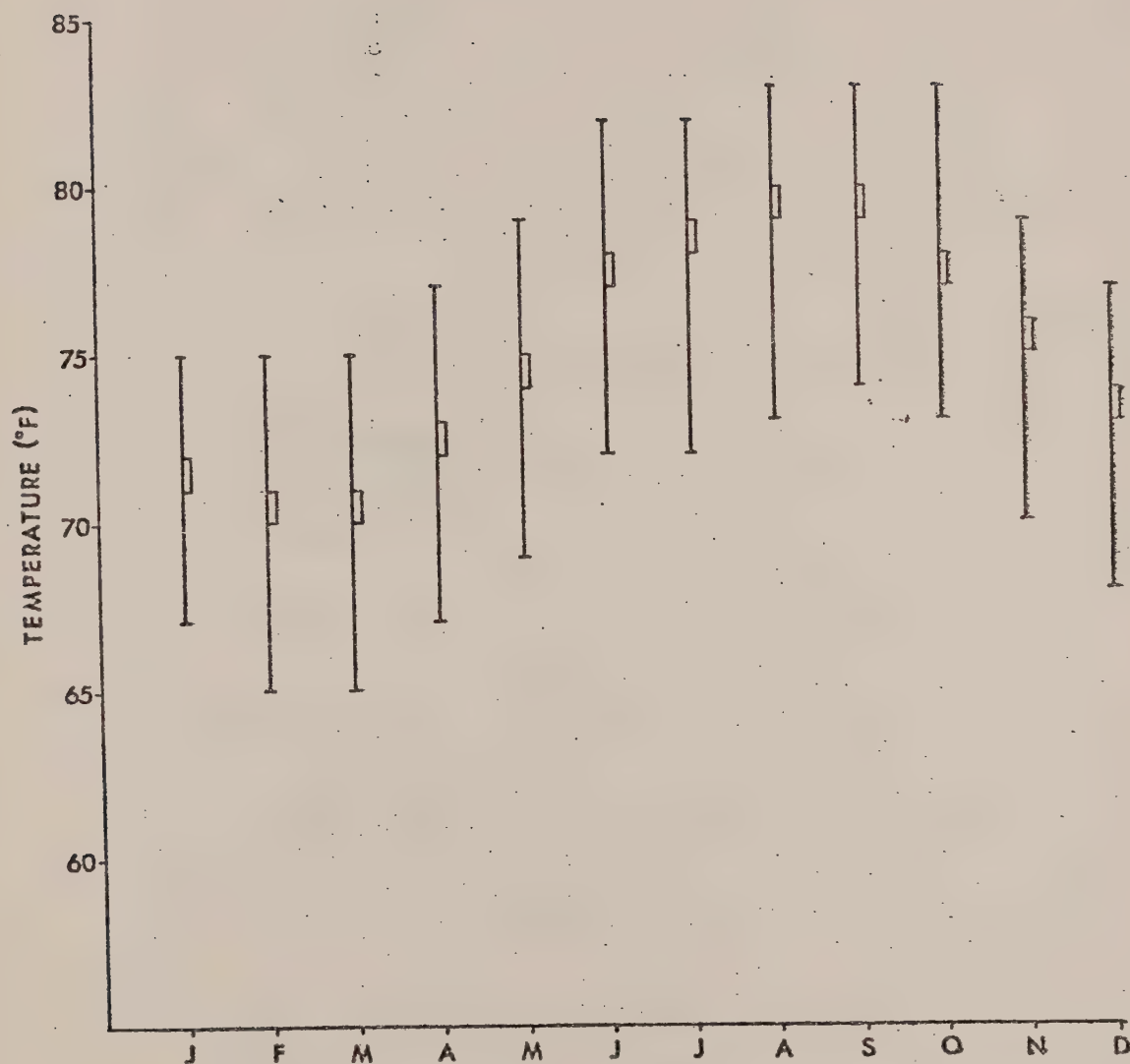


Figure 12.--The mode of the monthly means for a 12-year period, December 1950-December 1962, and the range of the maximum and minimum modes of temperature for French Frigate Shoals (Amerson 1971).

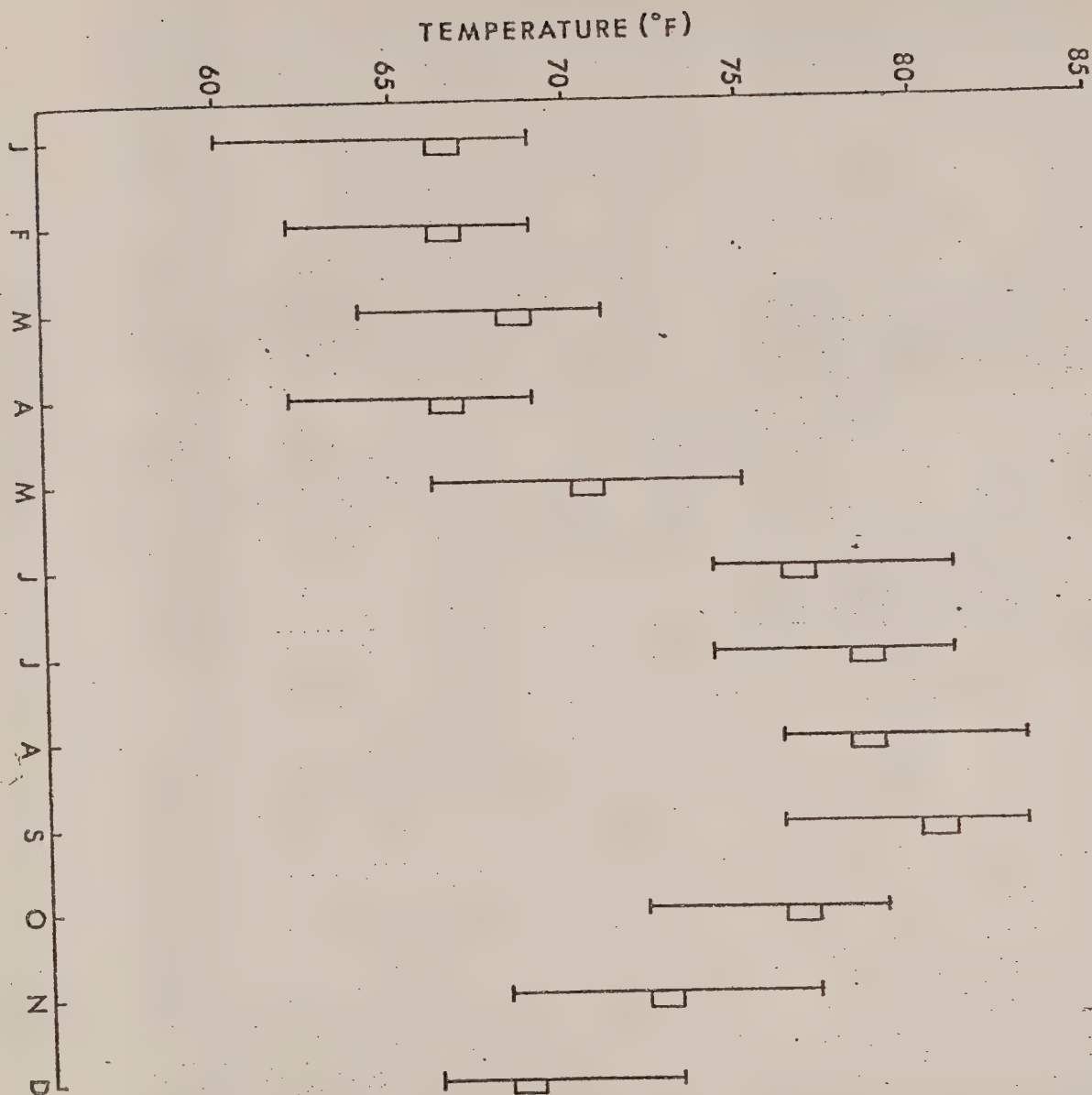
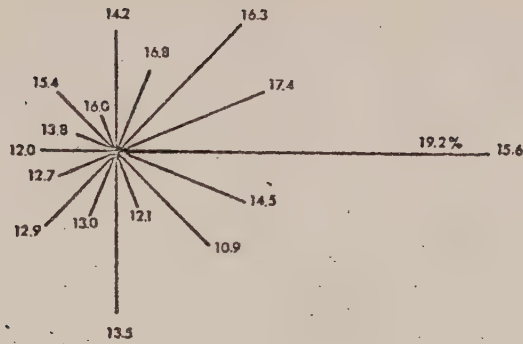
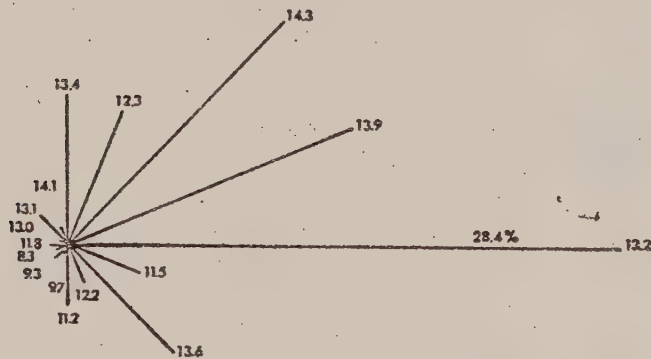


Figure 13.--Monthly temperature means and their maximum and minimum ranges for a 10-year period, 1953 to 1963, at Midway Atoll. (Amerson, Clapp and Wirtz 1974).

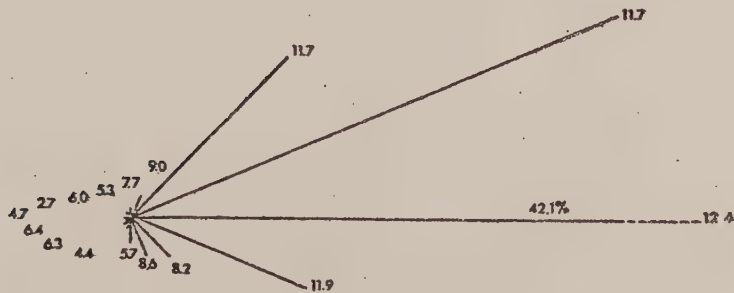
Winter



Spring



Summer



Autumn

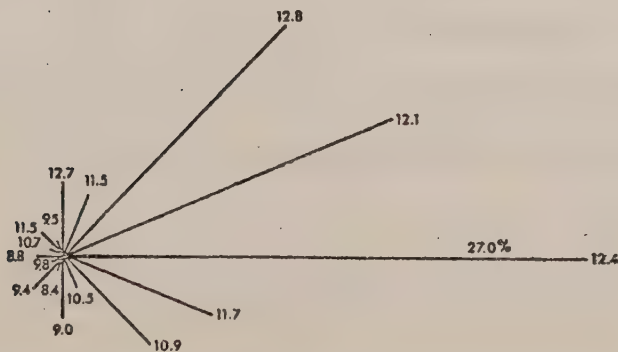


Figure 14.--Wind direction and speed at French Frigate Shoals from December 1950 to December 1962. Length of directional line indicates percent of observations from that direction; figure at end of directional line is mean wind speed in knots (Amerson 1971).

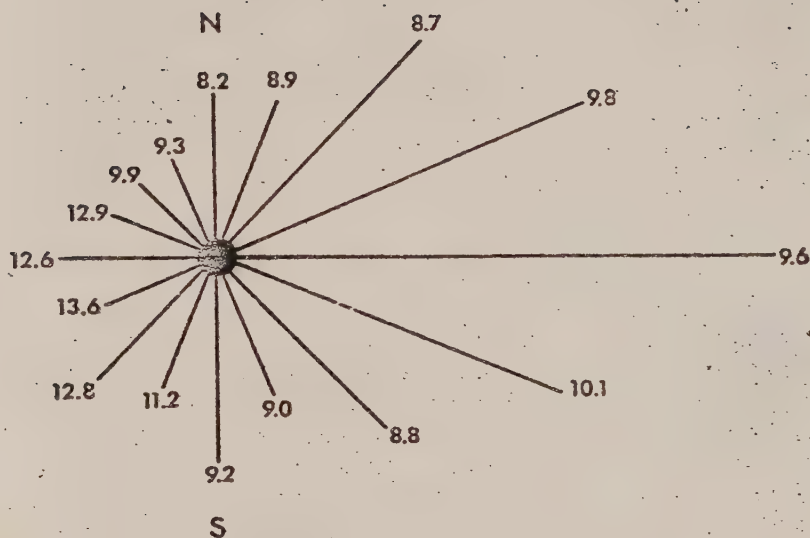


Figure 15.--Wind direction and speed at Midway Atoll from 1953 to 1963.

Length of directional line indicates percent of observations from that direction; figure at end of directional line is mean wind speed in knots. (Amerson, Clapp and Wirtz 1974).

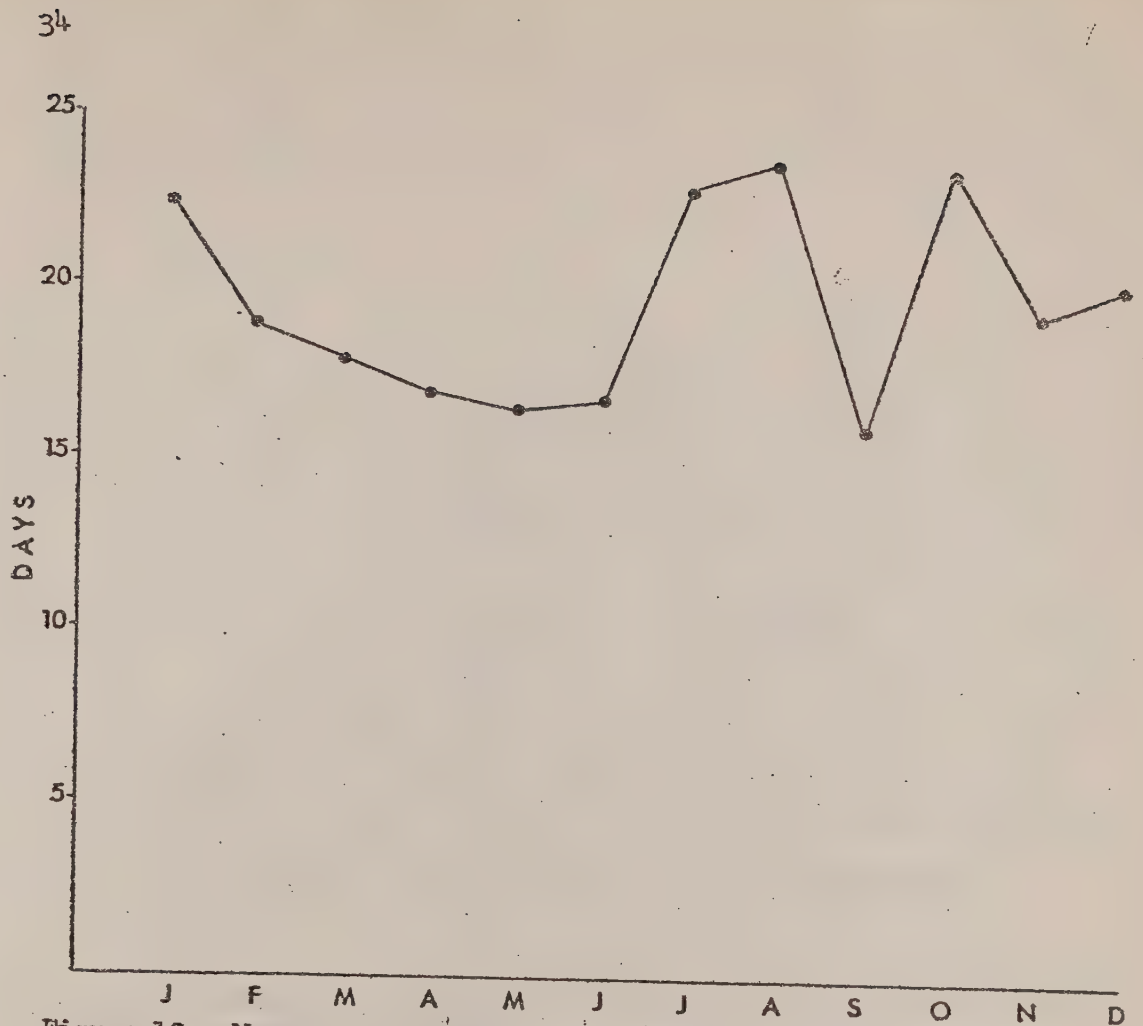


Figure 16.--Mean number of days with measurable precipitation for French Frigate Shoals, June 1954-January 1960, March 1960-December 1962 (Amerson 1971).

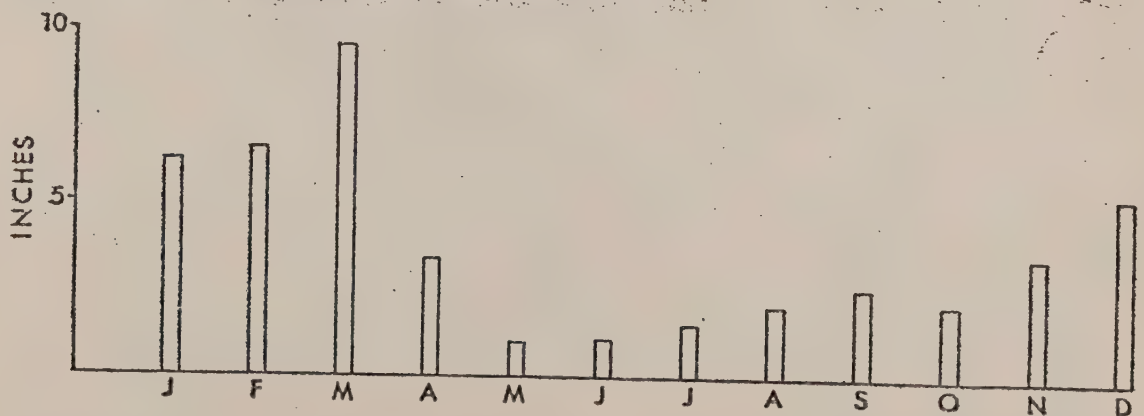


Figure 17.--Mean monthly precipitation in inches for French Frigate Shoals, June 1954-January 1960, March 1960-December 1962 (Amerson 1971).

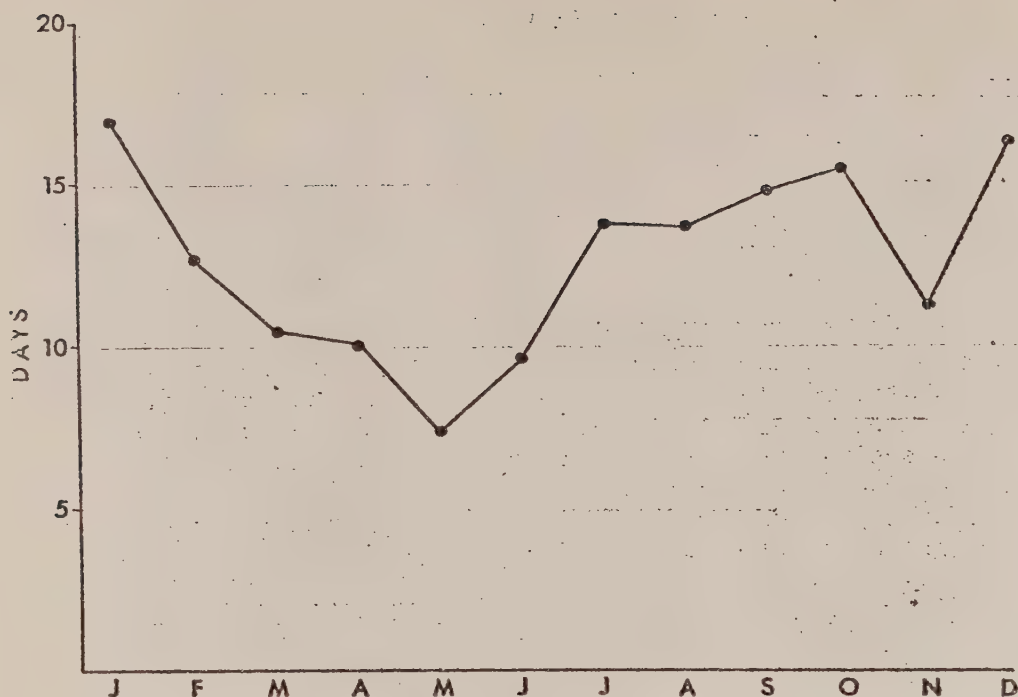
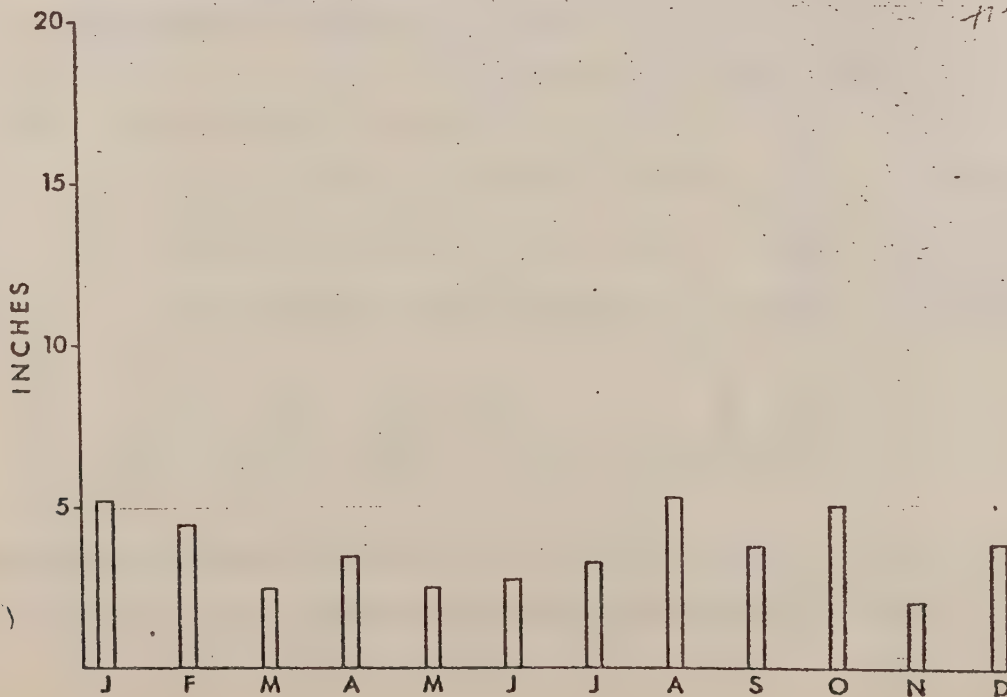


Figure 18.—Mean number of days with measurable precipitation for Midway Atoll, 1953 to 1963 (Amerson, Clapp and Wirtz 1974).

Figure 19.—Mean monthly precipitation in inches for Midway Atoll, 1953 to 1963 (Amerson, Clapp and Wirtz 1974).



BCF-1963
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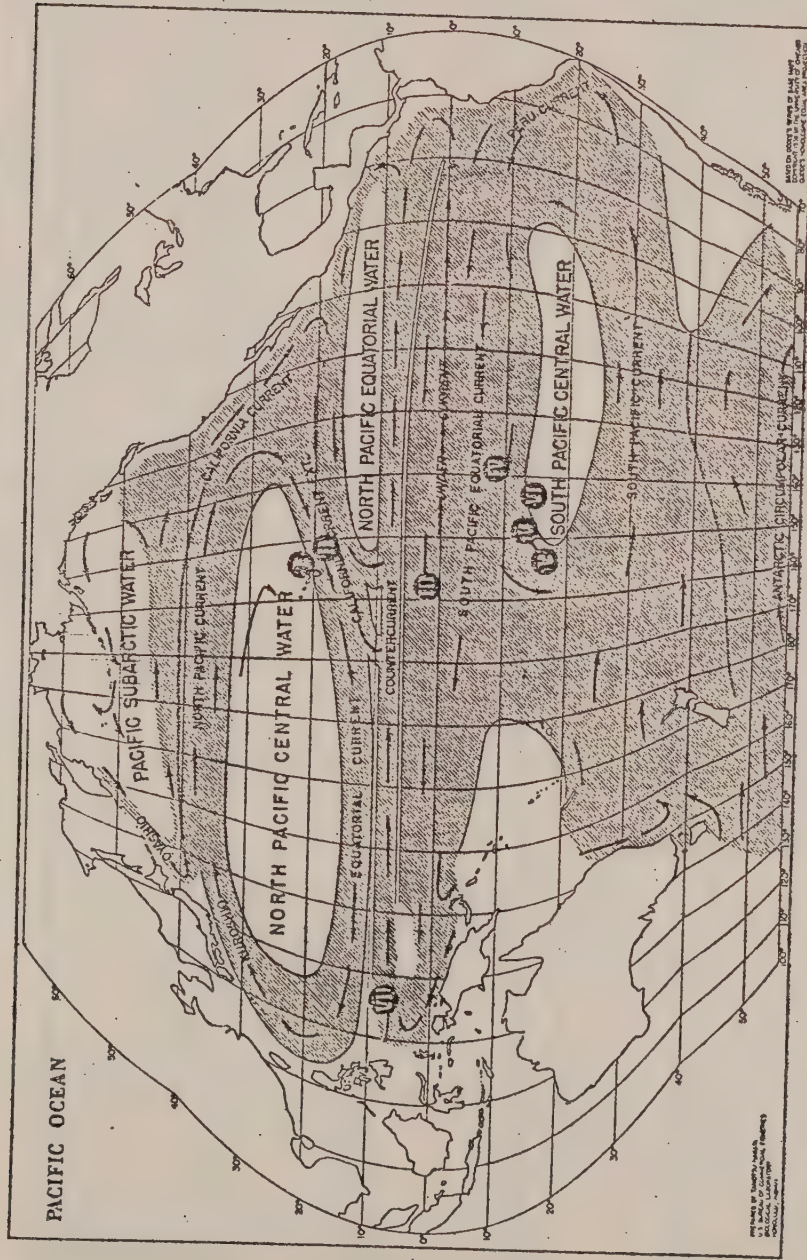


Figure 20.--Major circulation features of the Pacific Ocean (Bureau of Commercial Fisheries 1963).

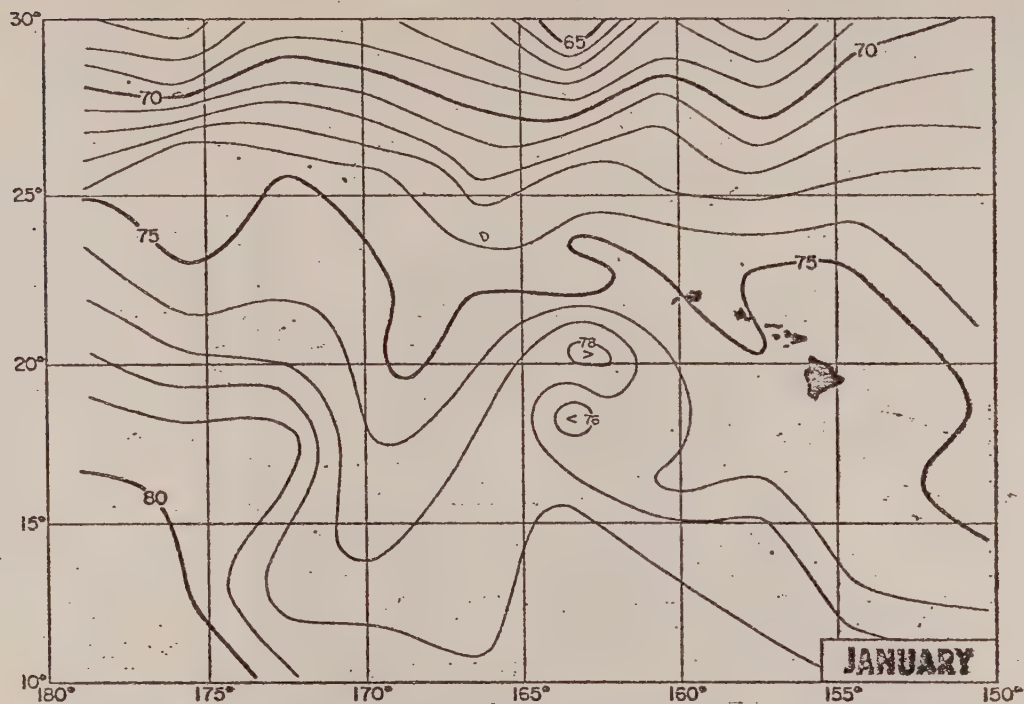


Figure 2la.--Distribution of surface temperature ($^{\circ}\text{F}$) in January (Seckel 1962).

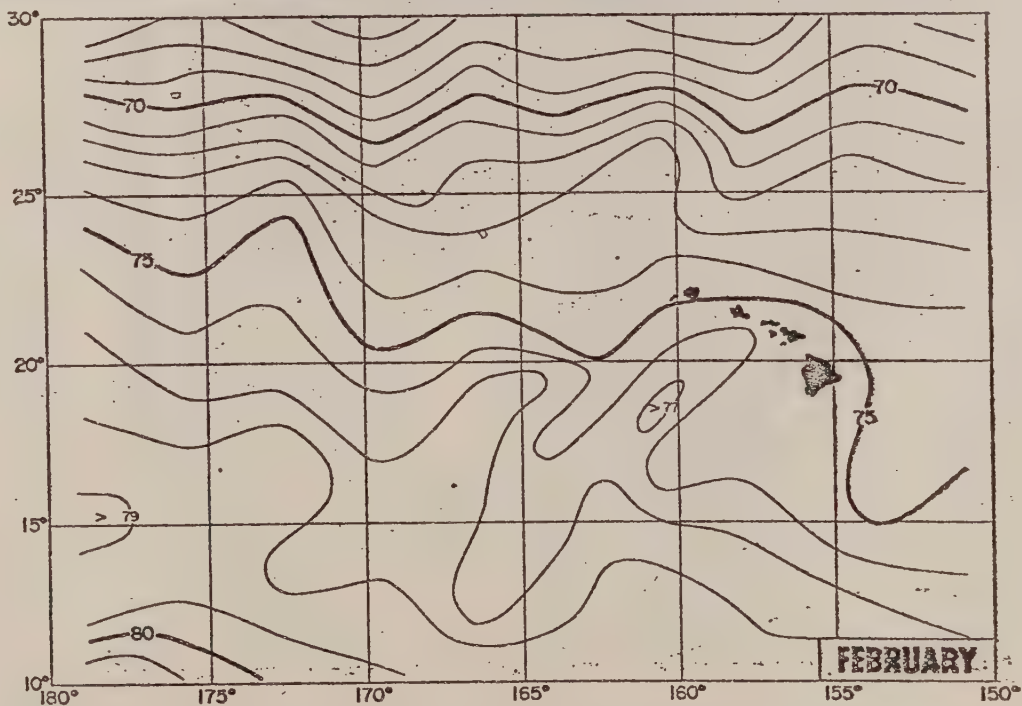


Figure 2lb.--Distribution of surface temperature ($^{\circ}\text{F}$) in February (Seckel 1962)

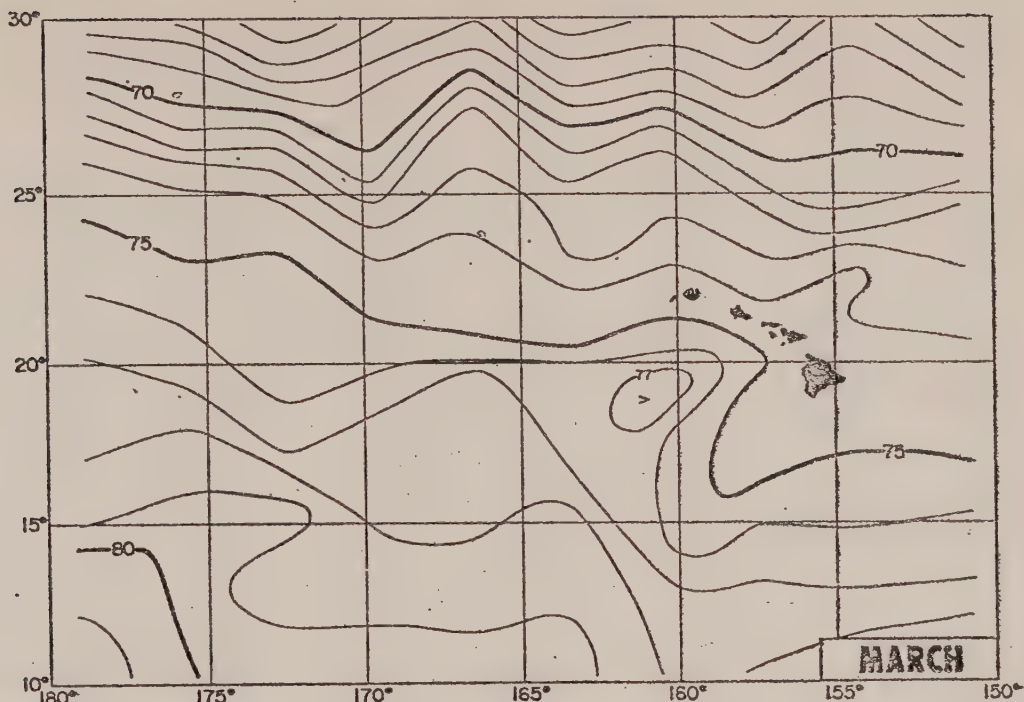


Figure 21c.--Distribution of surface temperature ($^{\circ}\text{F}$) in March (Seckel 1962).

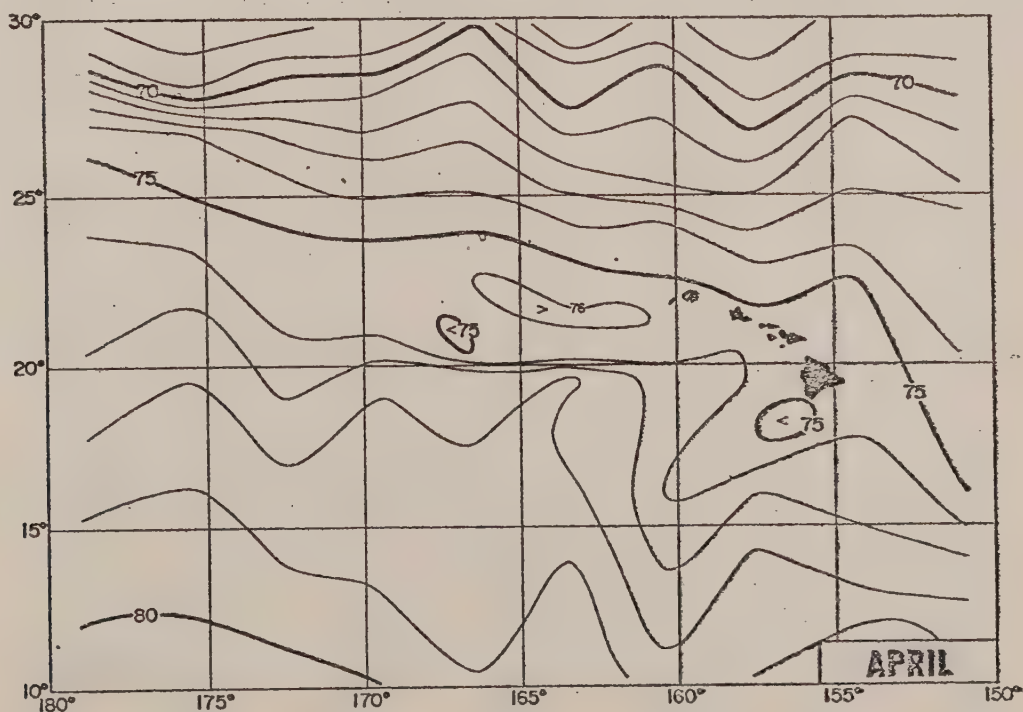


Figure 21d.--Distribution of surface temperature ($^{\circ}\text{F}$) in April (Seckel 1962).

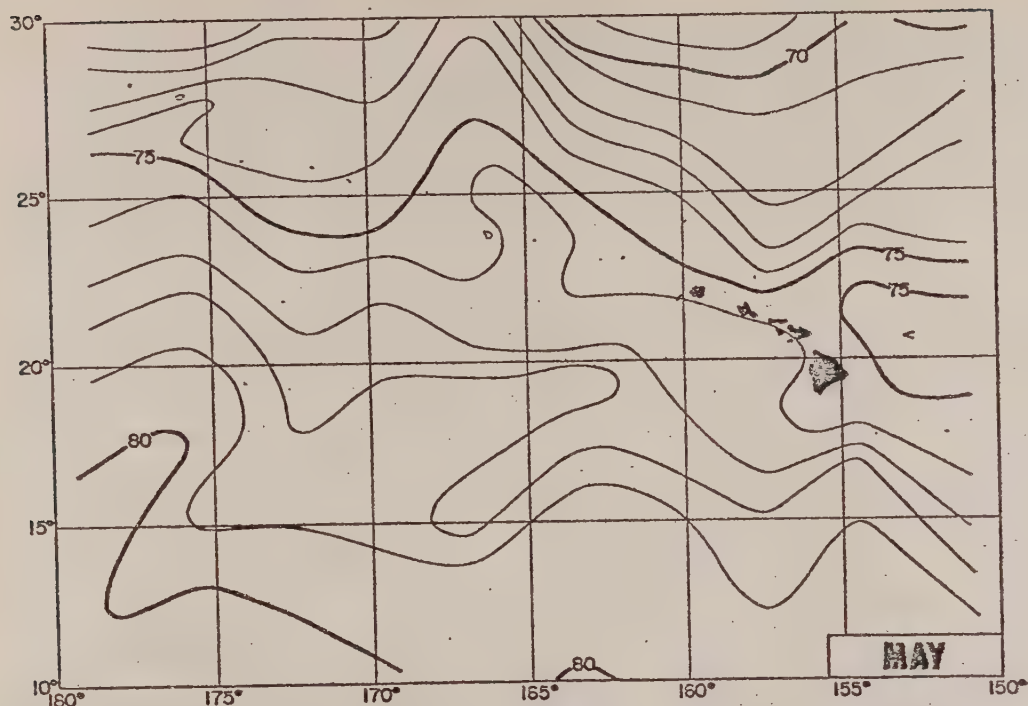


Figure 21e.--Distribution of surface temperature ($^{\circ}\text{F}$) in May (Seckel 1962).

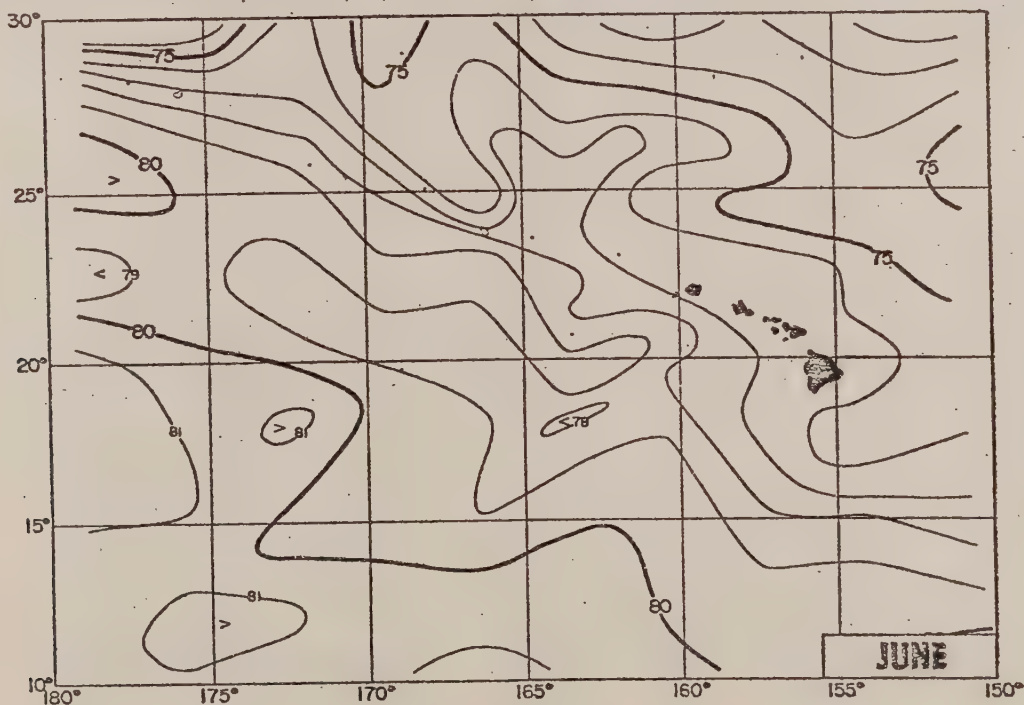


Figure 21f.--Distribution of surface temperature ($^{\circ}\text{F}$) in June (Seckel 1962).

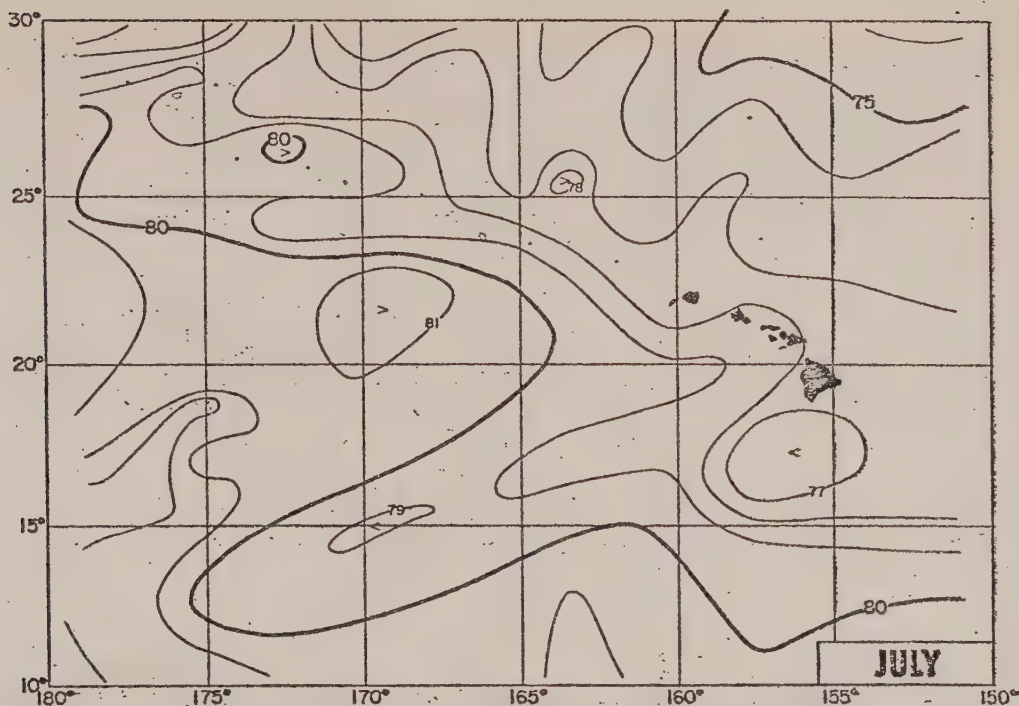


Figure 2lg.--Distribution of surface temperature ($^{\circ}$ F) in July (Seckel 1962).



Figure 2lh.--Distribution of surface temperature ($^{\circ}$ F) in August (Seckel 1962).

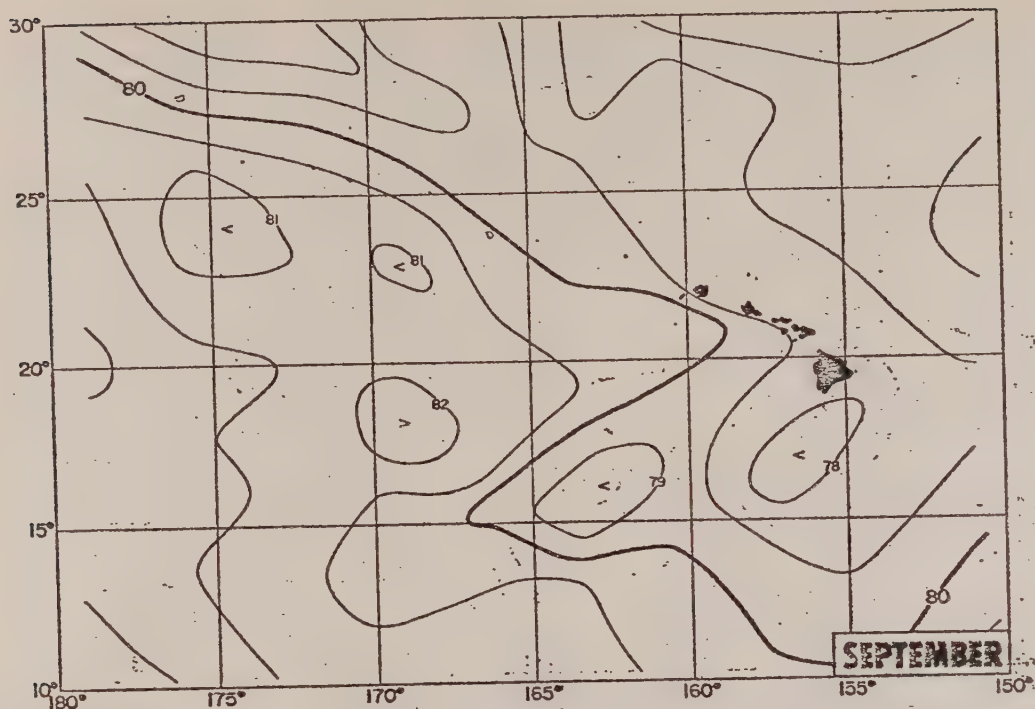


Figure 21i.--Distribution of surface temperature (°F) in September (Seckel 1962)

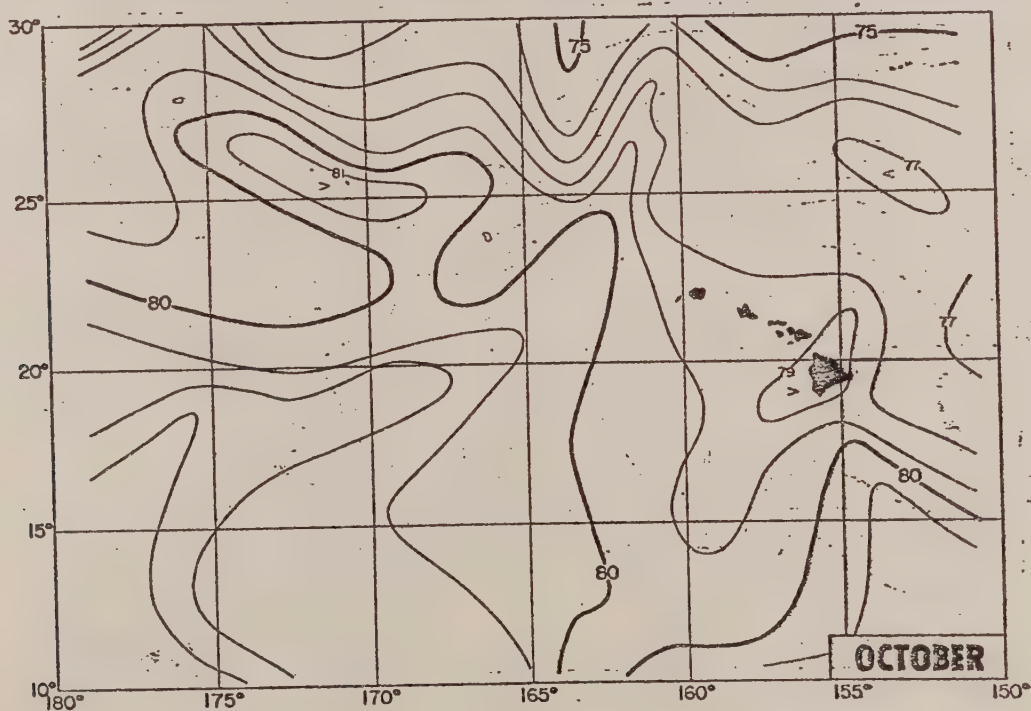


Figure 21j.--Distribution of surface temperature (°F) in October (Seckel 1962)

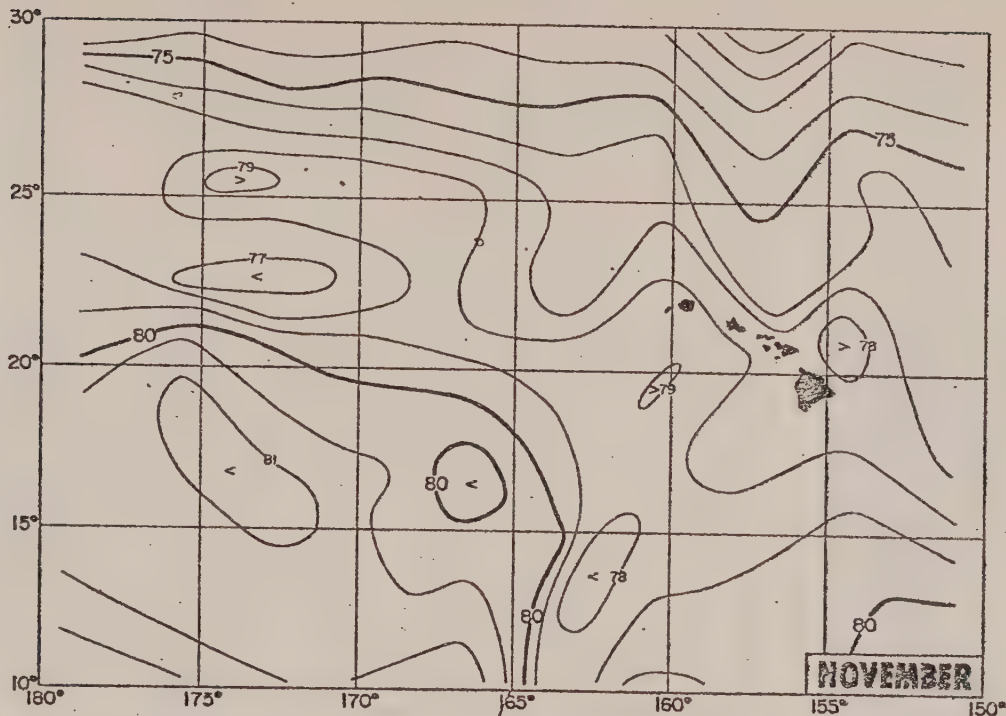


Figure 21k.--Distribution of surface temperature ($^{\circ}$ F) in November (Seckel 1962).

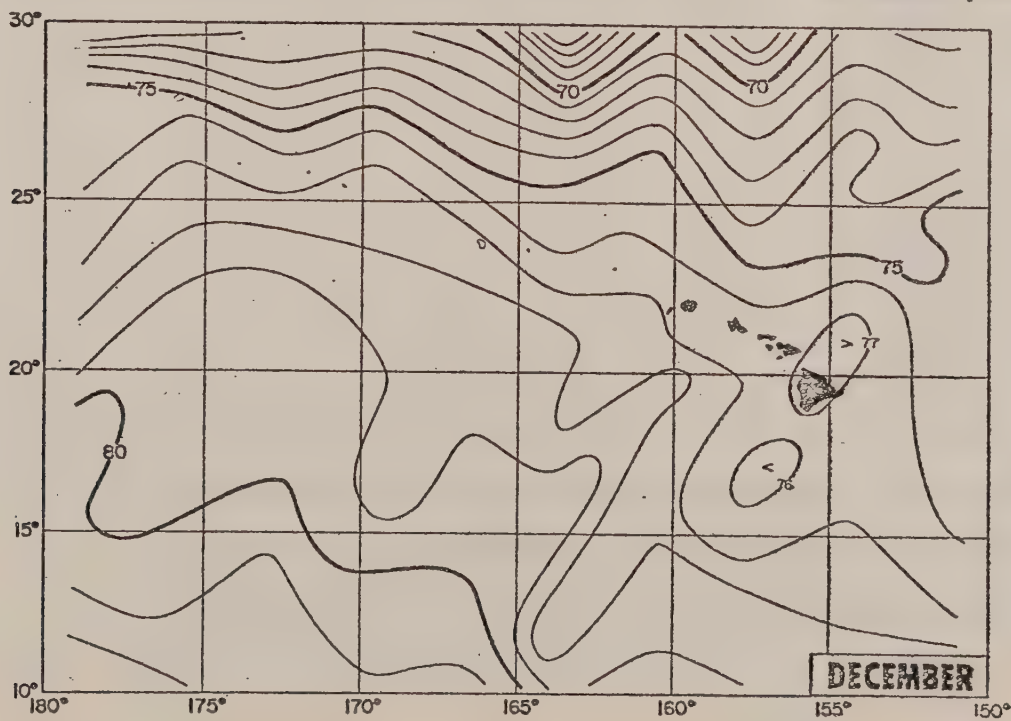


Figure 21l.--Distribution of surface temperature ($^{\circ}$ F) in December (Seckel 1962).

Seckel 1962

Fig. 22

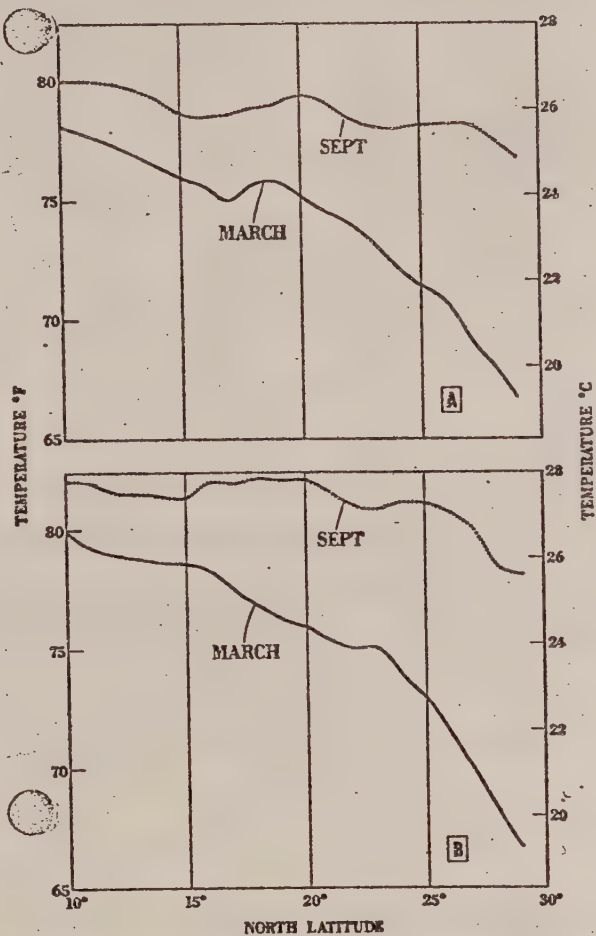


Figure 22.—Meridional profile of the surface temperature in March and September, lat. 10° to 30° N: Panel A, long. 153° - 161° W; Panel B, long. 168° - 176° W, (Seckel 1962).

Seckel 1962
Fig 23

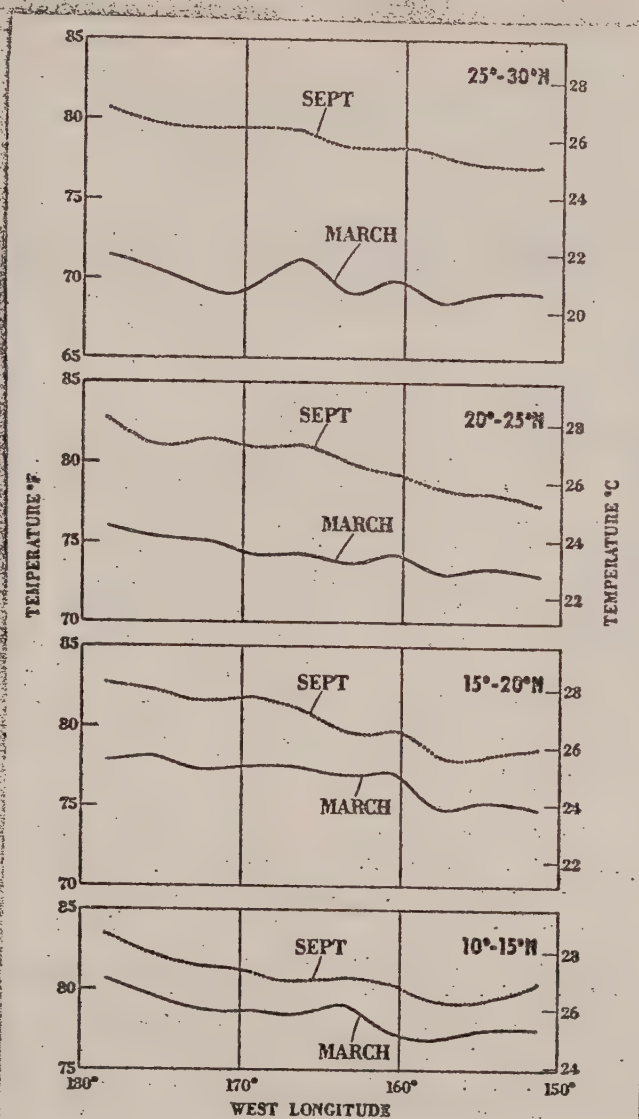


Figure 23.--Zonal profile of the surface temperature in March and September, lat. 10° - 15° N, lat. 15° - 20° N, lat. 20° - 25° N, lat. 25° - 30° N, and long. 150° W to 180° (Seckel 1962).

Seckel 1962
Fig. 24

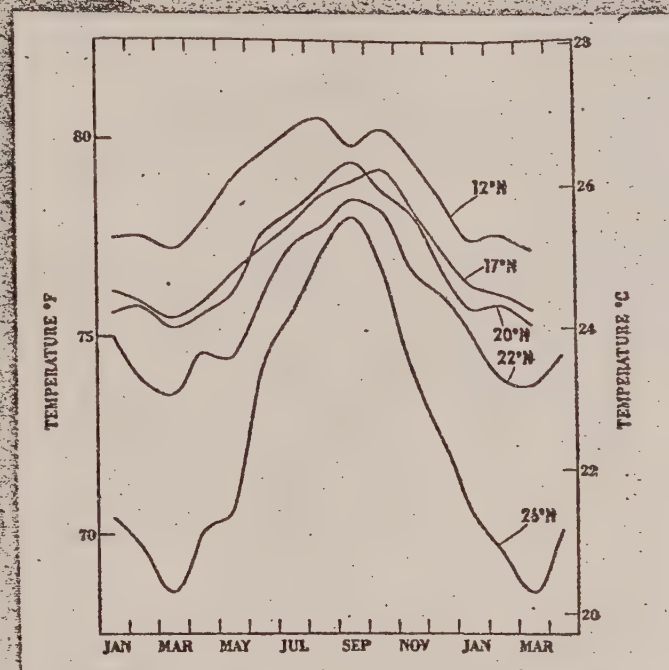


Figure 24.—Seasonal variation of the surface temperature at lat. 12° , lat. 17° , lat. 20° , lat. 22° and lat. 26° N between long. 153° and 161° W (Seckel 1962).

Seikel 1962

Figure 25a.--Distribution of the depth of the mixed layer (ft) in
January (Seikel 1962).

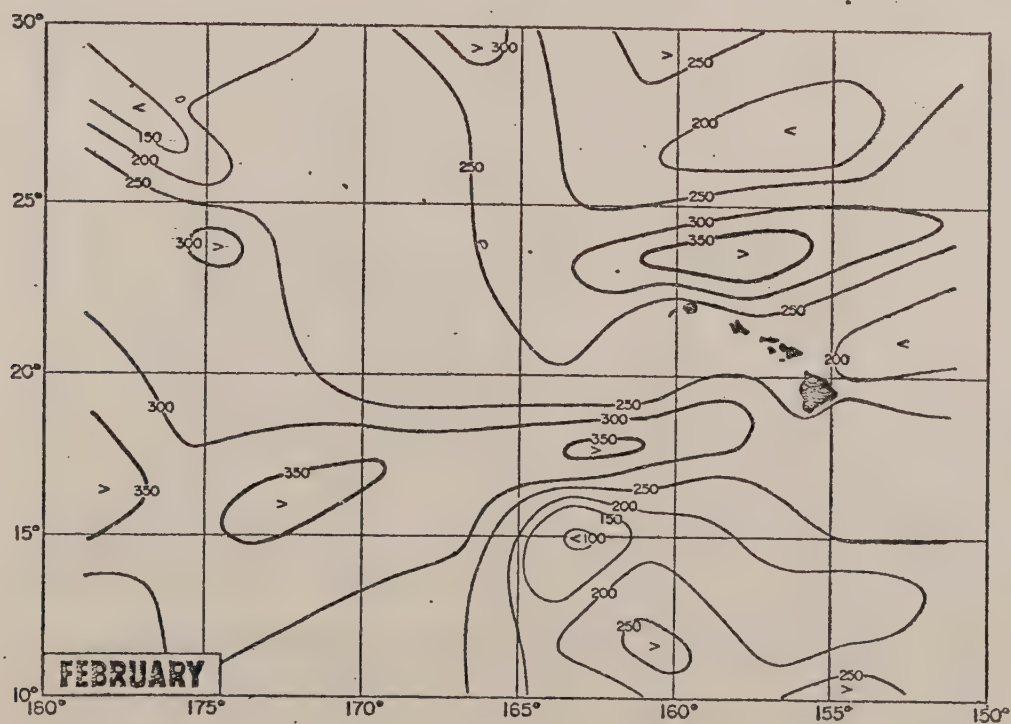
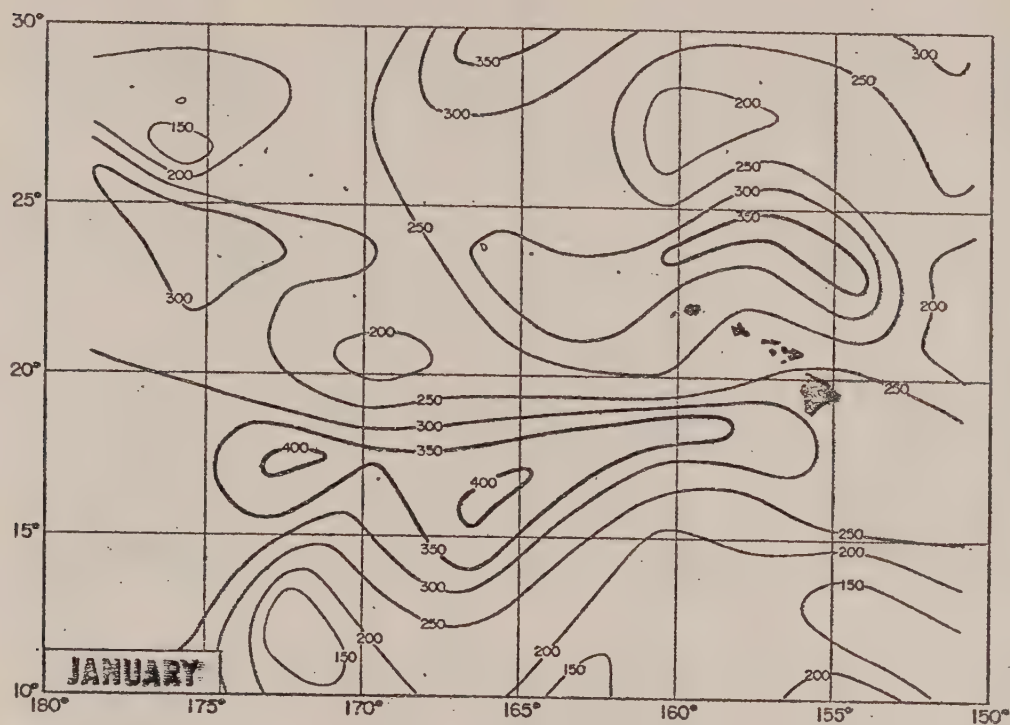


Figure 25b.--Distribution of the depth of the mixed layer (ft) in
February (Seikel 1962).

Figure 25c.--Distribution of the depth of the mixed layer (ft) in

March (Seckel 1962).

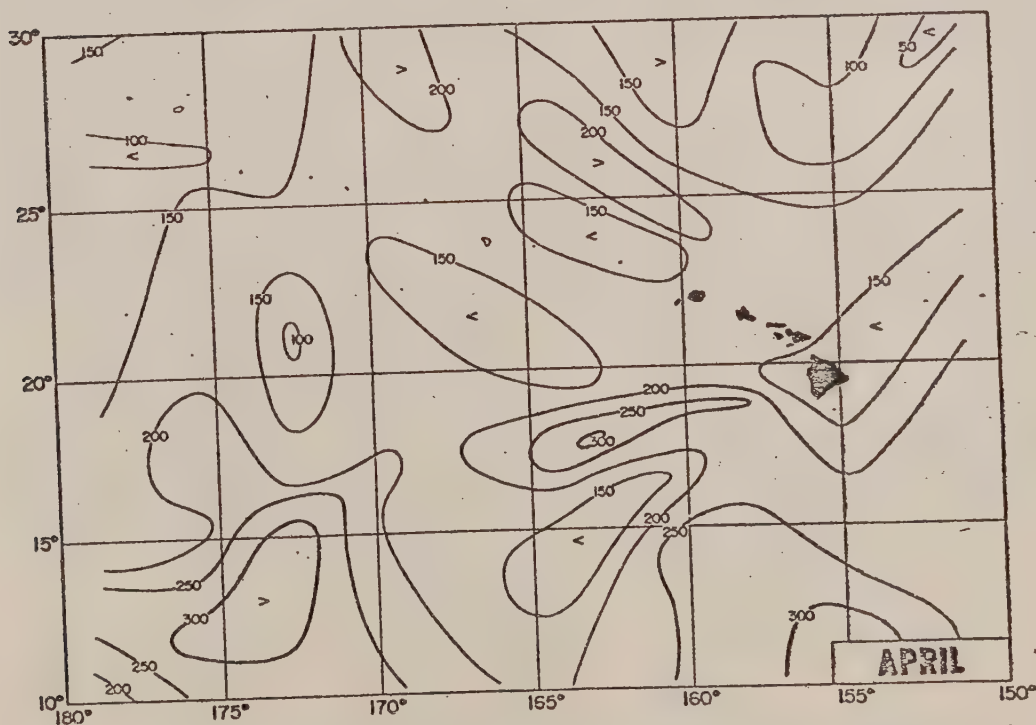
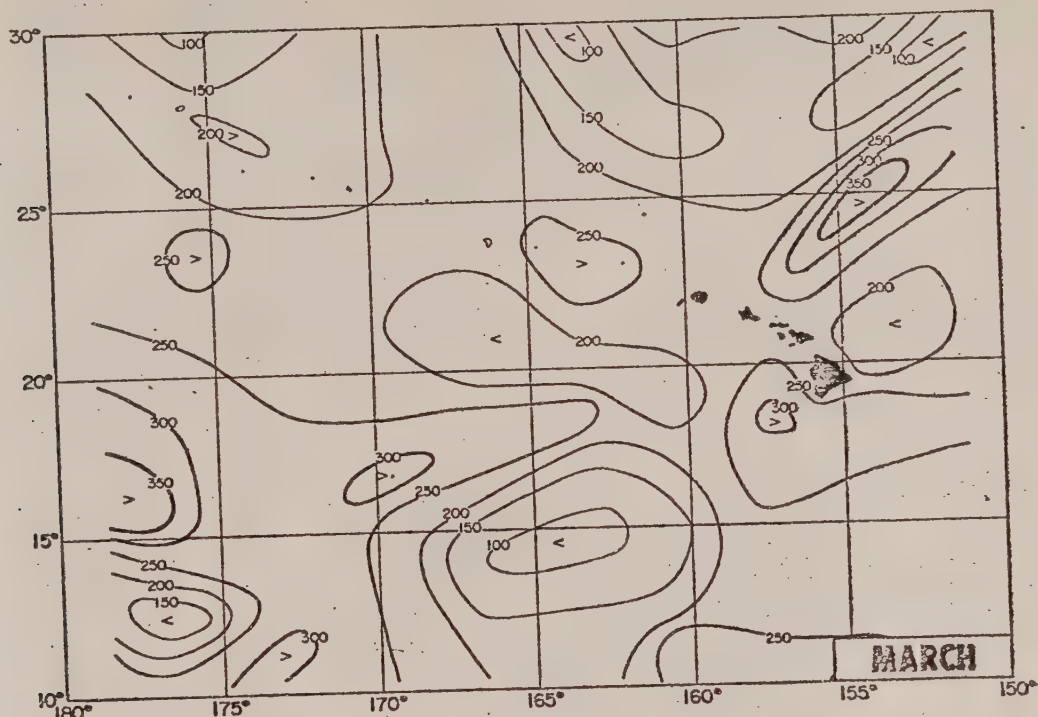


Figure 25d.--Distribution of the depth of the mixed layer (ft) in

April (Seckel 1962).

Figure 25e.—Distribution of the depth of the mixed layer (ft) in

May (Seckel 1962).

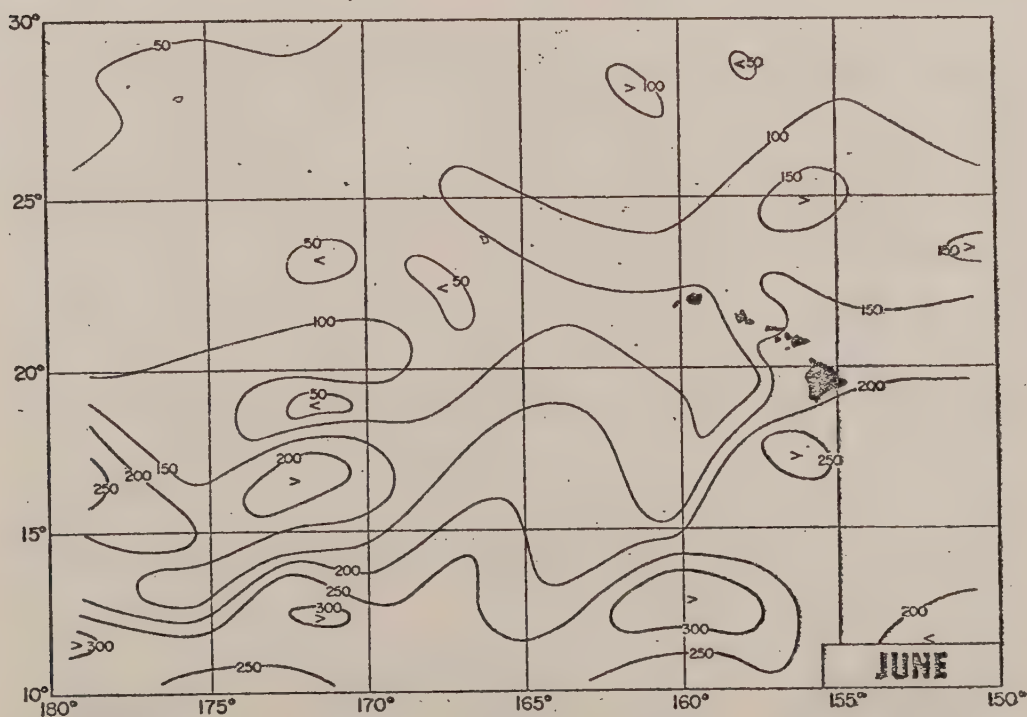
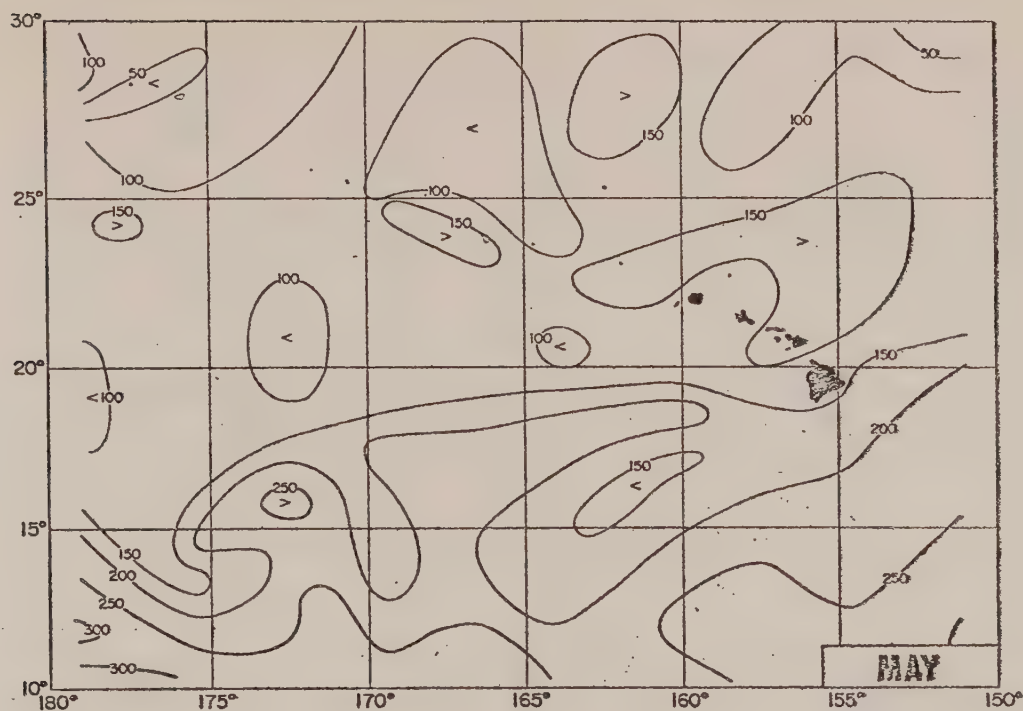


Figure 25f.—Distribution of the depth of the mixed layer (ft) in

June (Seckel 1962).

Figure 25g.—Distribution of the depth of the mixed layer (ft) in

July (Seckel 1962).

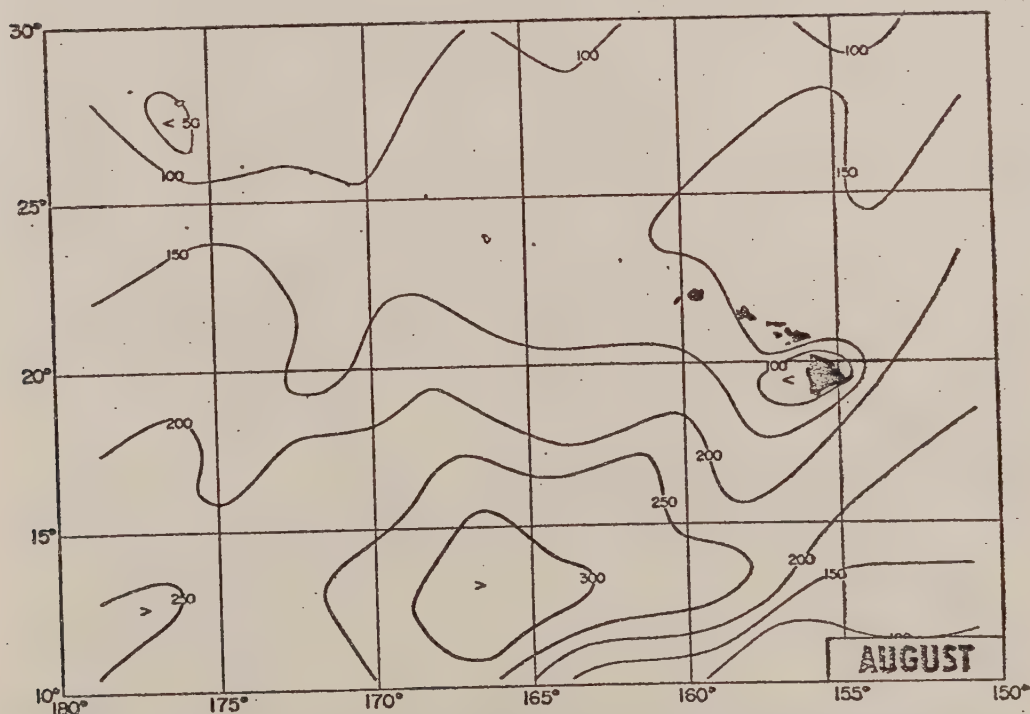
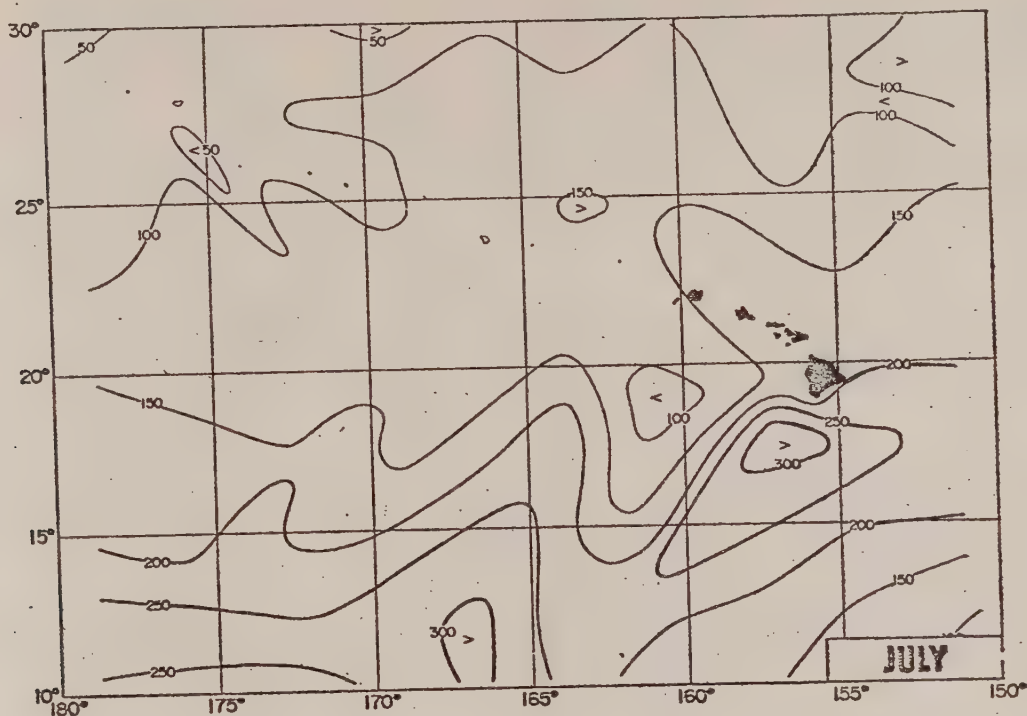


Figure 25h.—Distribution of the depth of the mixed layer (ft) in

August (Seckel 1962).

Figure 25i.--Distribution of the depth of the mixed layer (ft) in
September (Seckel 1962).

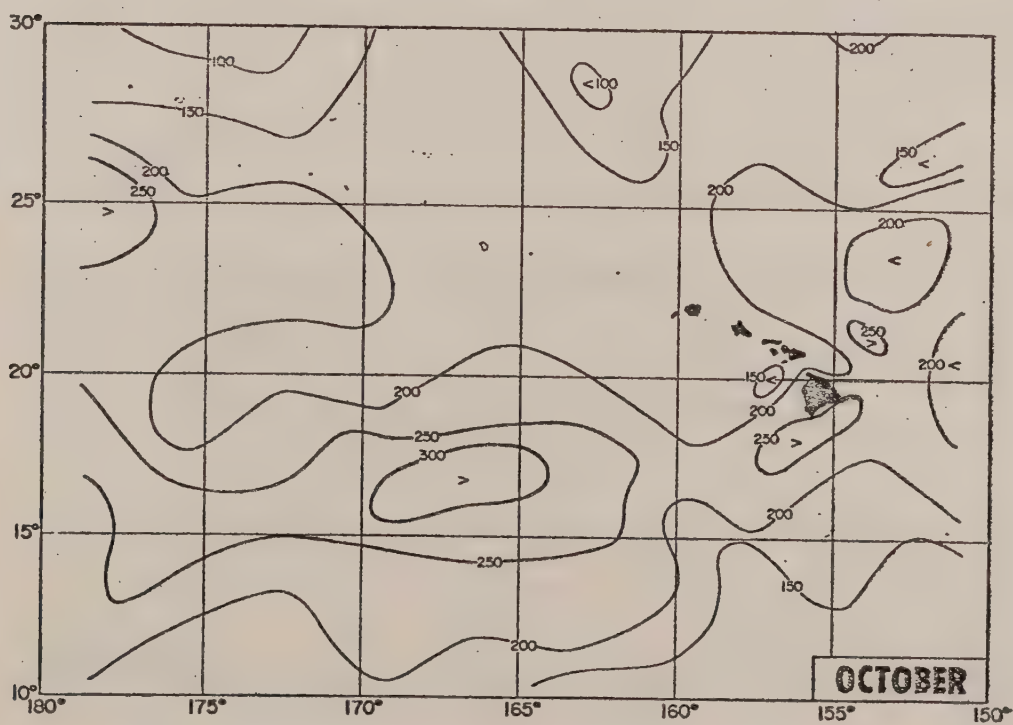
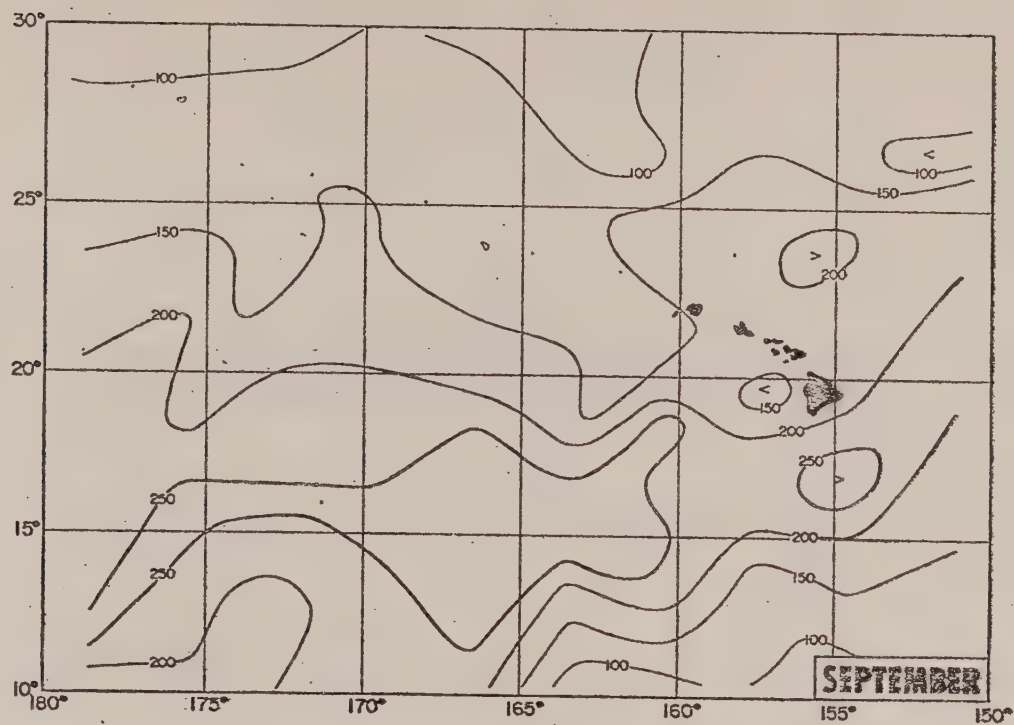


Figure 25j.--Distribution of the depth of the mixed layer (ft) in
October (Seckel 1962).

Figure 25k.--Distribution of the depth of the mixed layer (ft) in

November (Seckel 1962)..

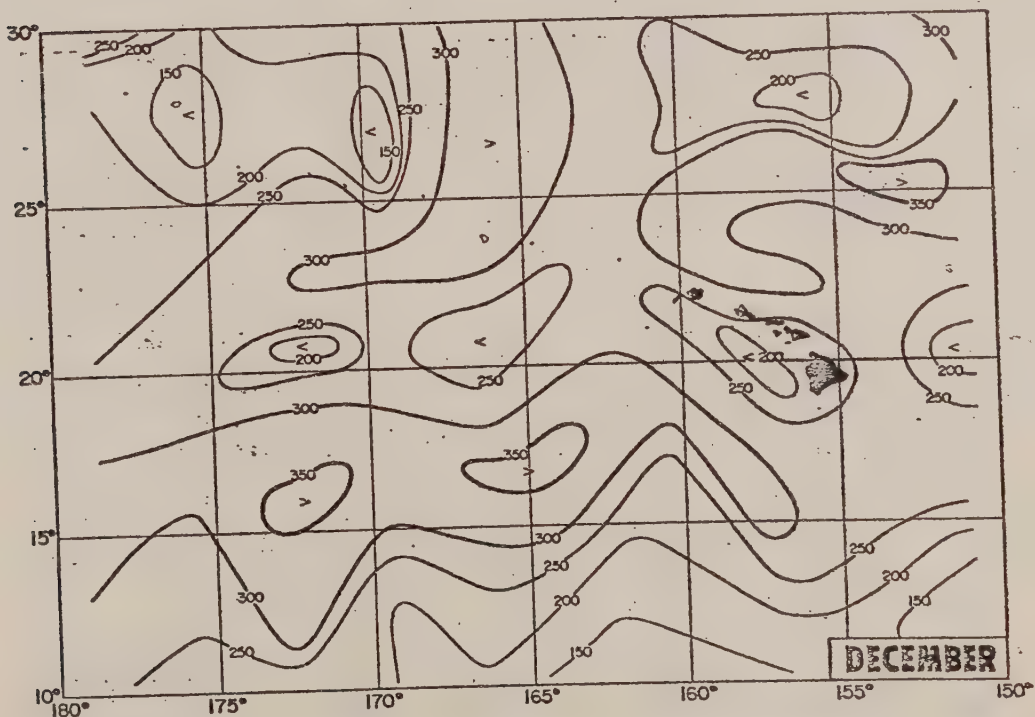
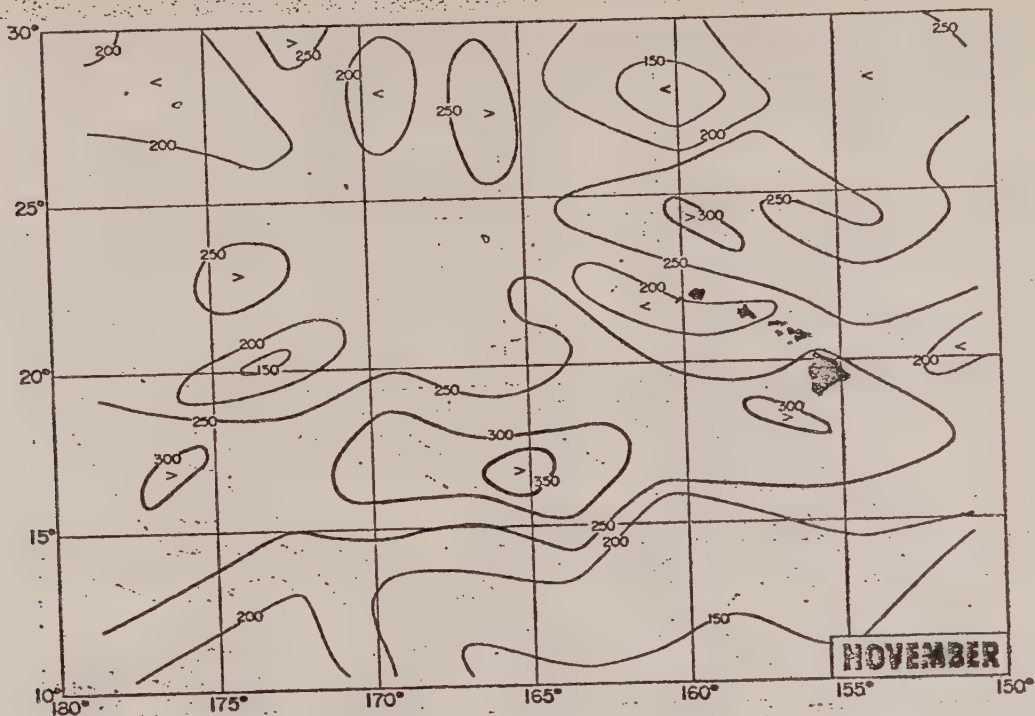


Figure 25l.--Distribution of the depth of the mixed layer (ft) in

December (Seckel 1962).

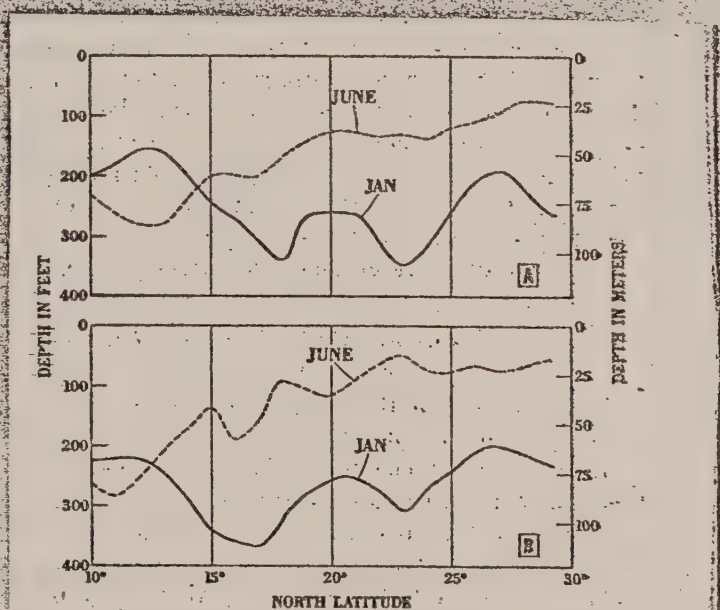


Figure 26.—Meridional profile of the depth of mixed layer in January and June, lat. 10° to 30° N. Panel A, long. 153° - 161° W; panel B, long. 168° - 176° W. (Seckel 1962).

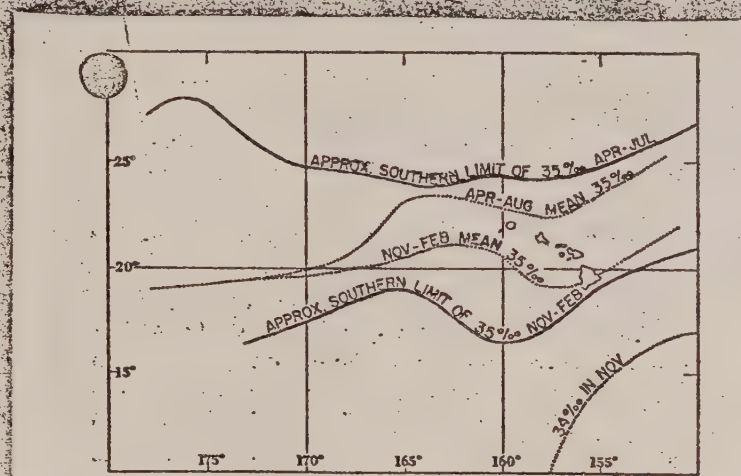


Figure 27.--Southern limit of the 35 ‰ salinity isopleth in April-July and November-February, and mean location of the 35 ‰ salinity isopleth in April-August and November-February (Seckel 1962).

Seckel 1962
Fig. 28 ~~285~~

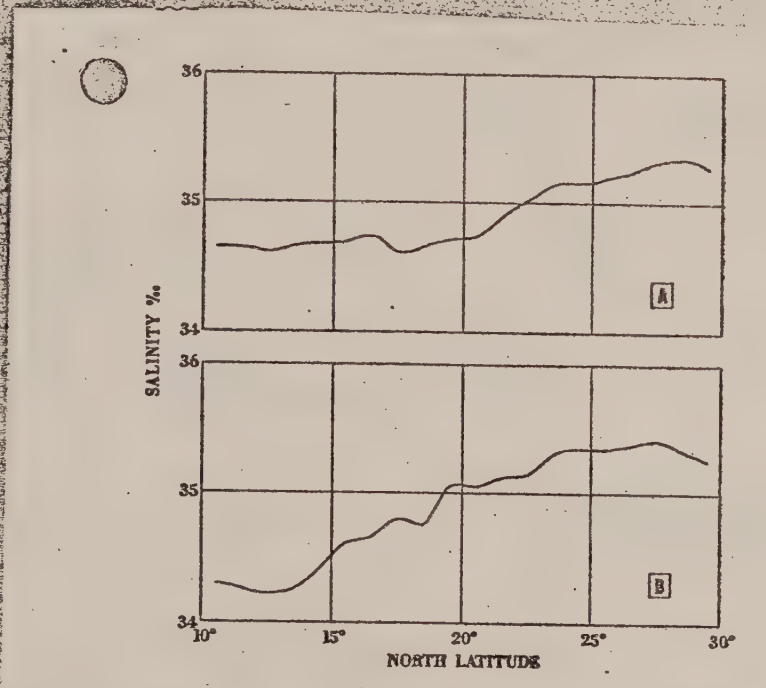


Figure 28.—Mean meridional salinity profile at lat. 10° to 30° N between long. 155° and 160° W. Panel A, April to August; panel B, November to February (Seckel 1962).

Figure 29a.—Distribution of surface salinity (o/oo) in April-August

(Seckel 1962).

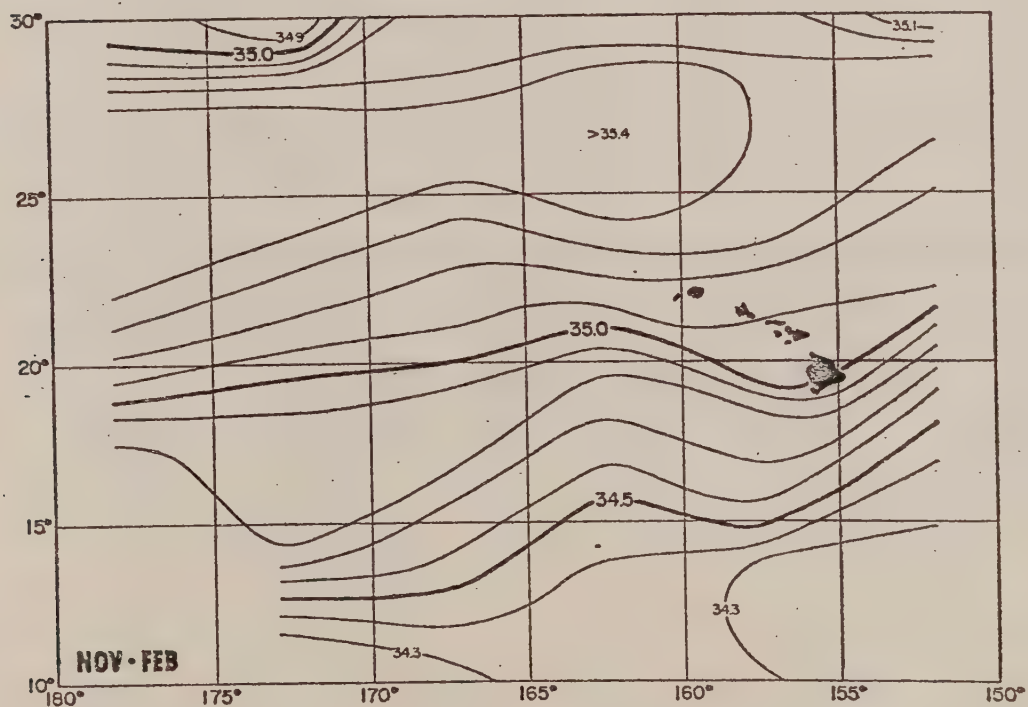
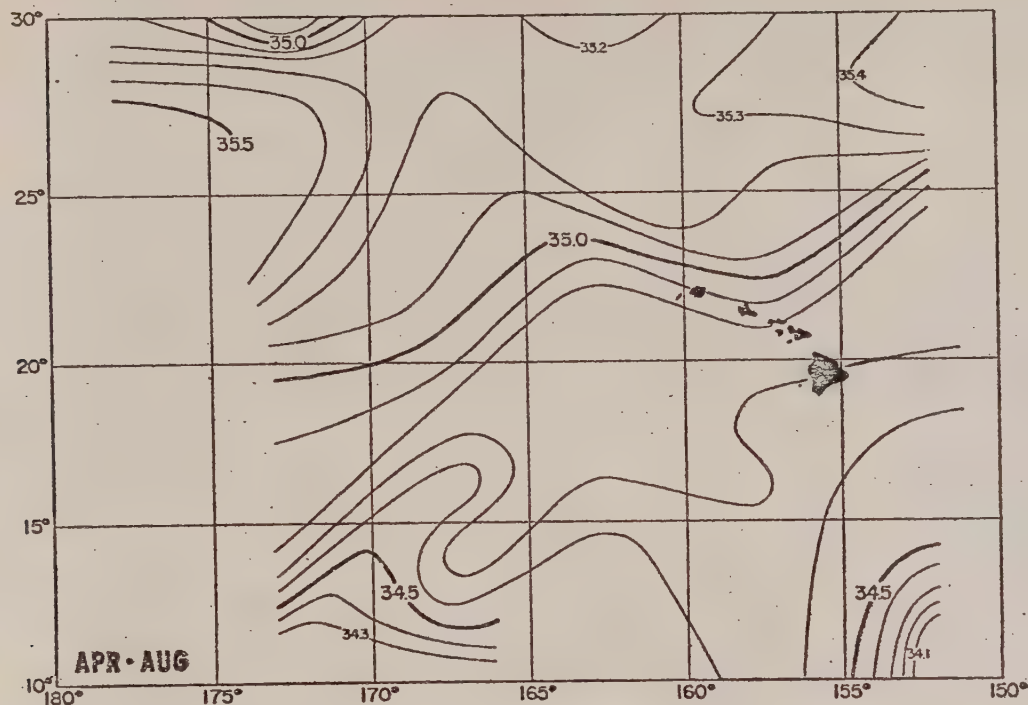
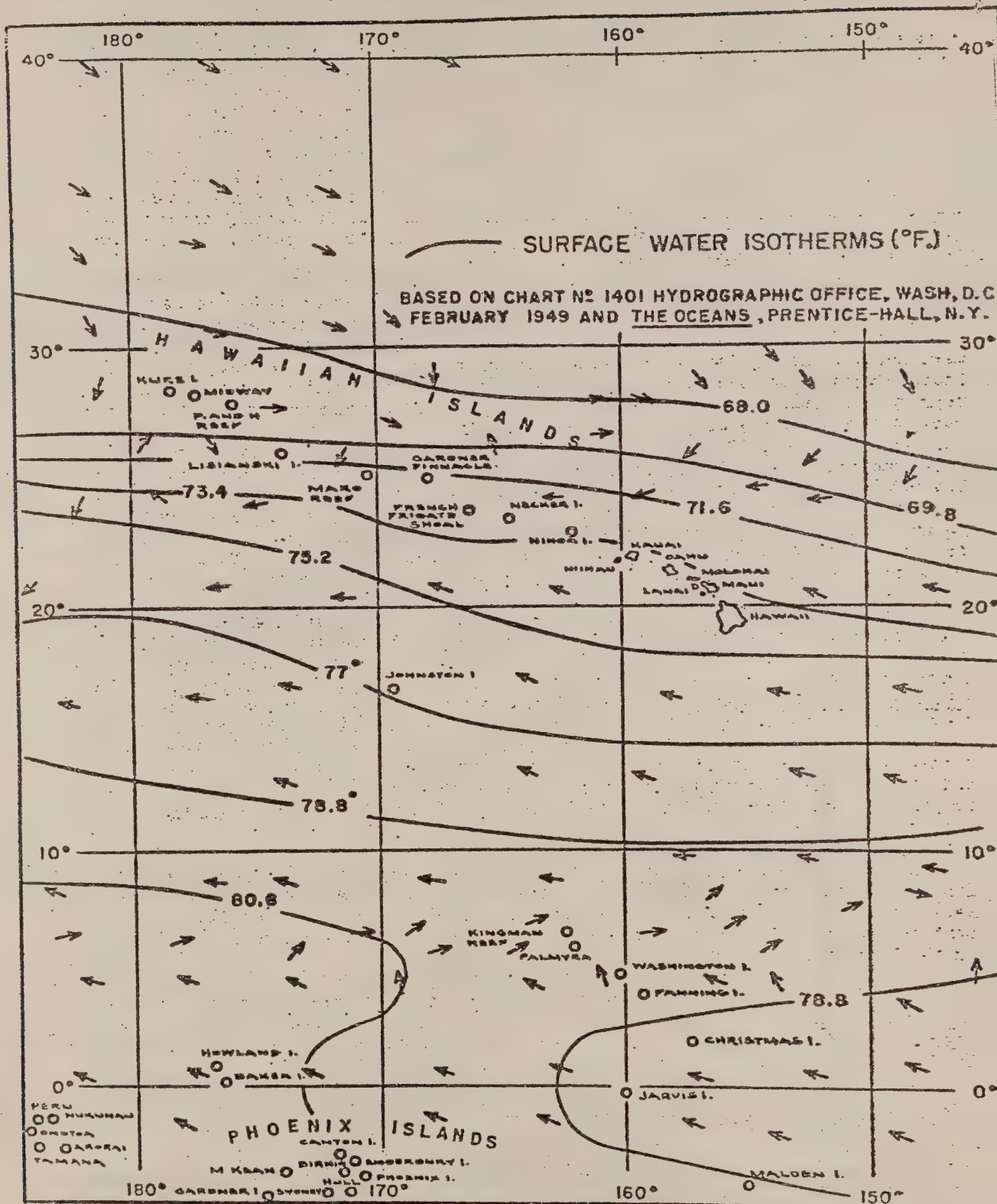


Figure 29b.—Distribution of surface salinity (o/oo) in November-February

(Seckel 1962).



U.S. Navy Hydrographic Office
1950

Figure 31a.—Surface drift vectors for January (U. S. Navy Hydrographic Office 1950).

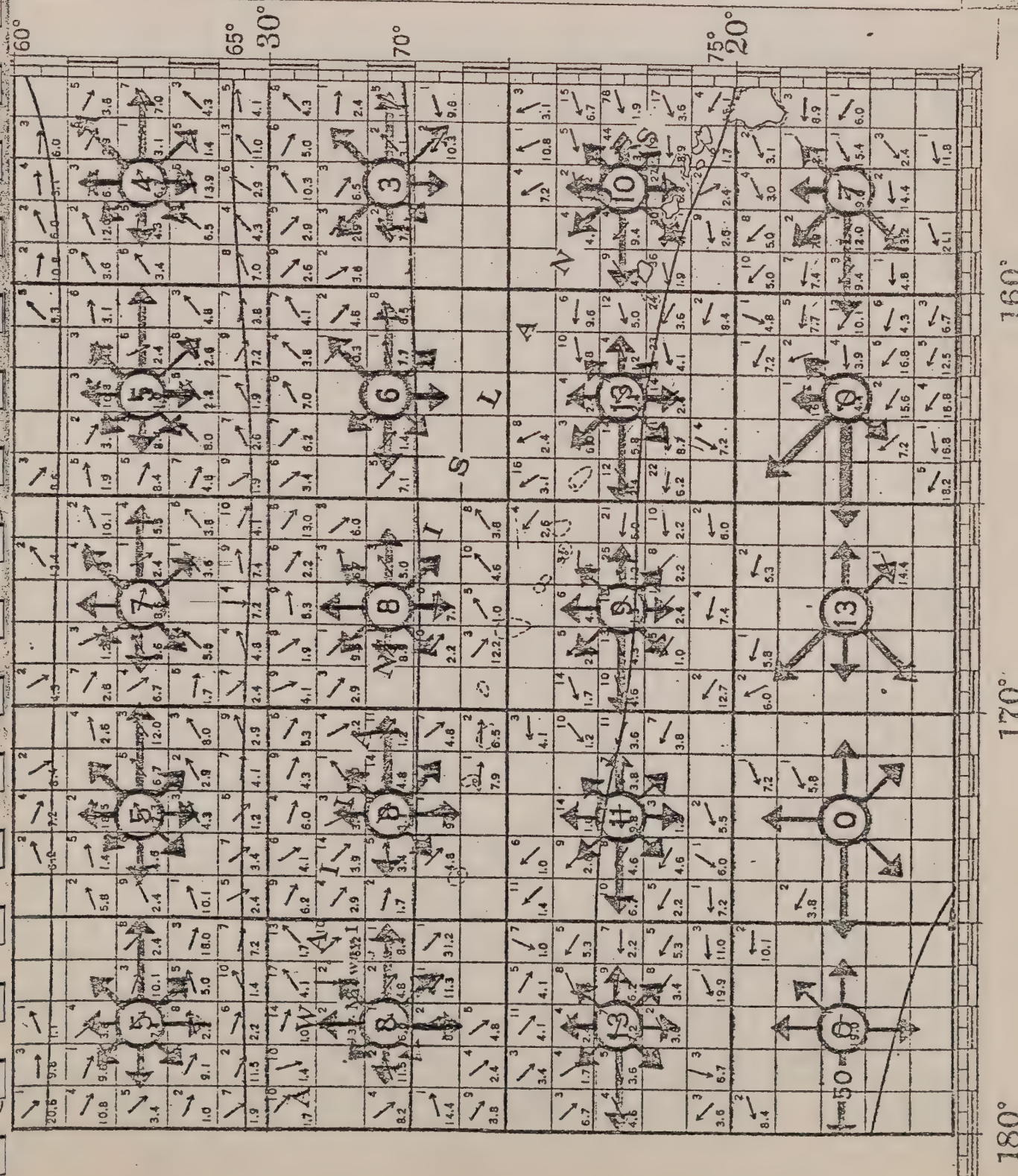


Figure 31d.—Surface drift vectors for April (U. S. Navy Hydrographic Office 1950).

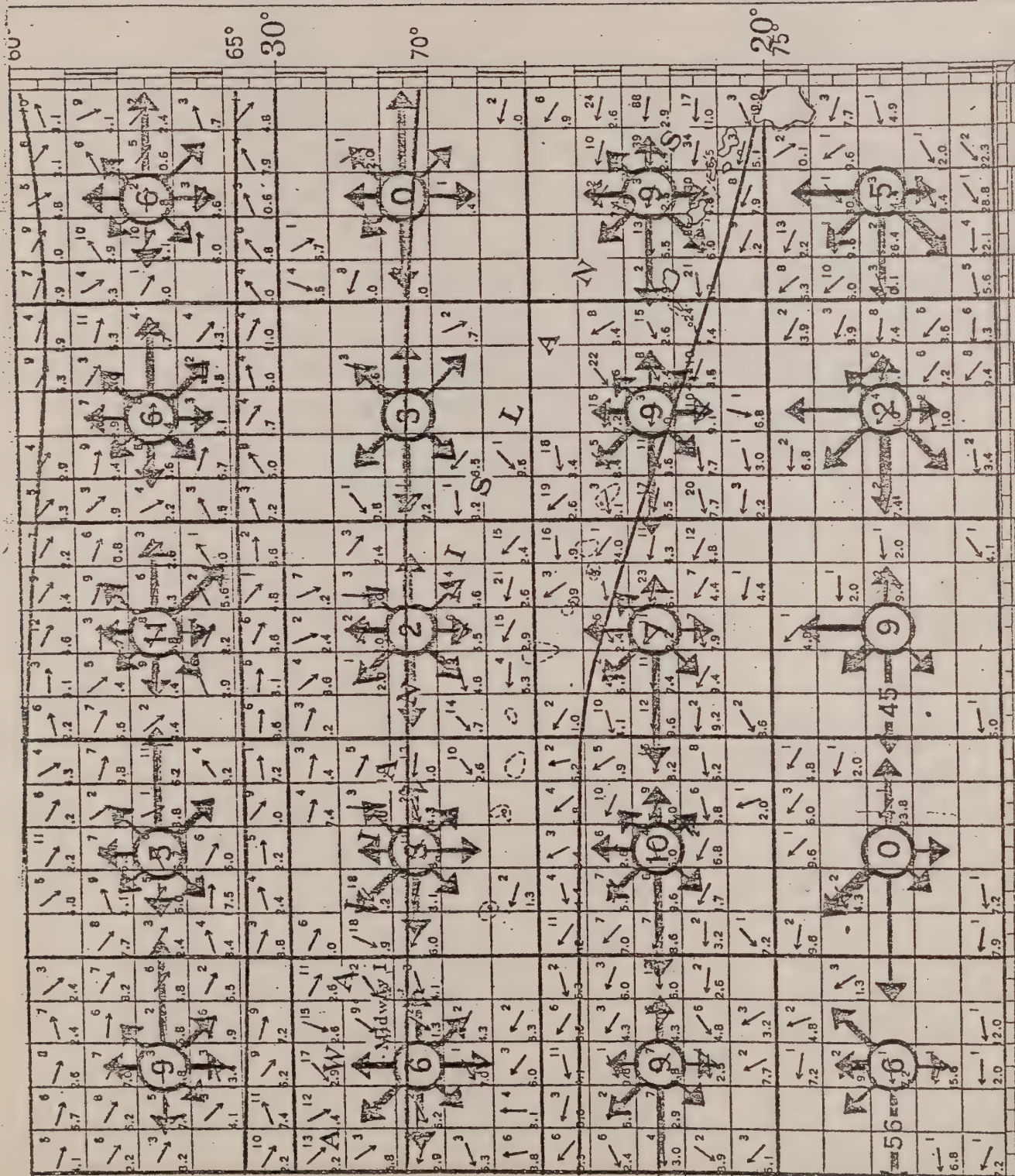


Figure 31e.—Surface drift vectors for May (U. S. Navy Hydrographic Office 1950).

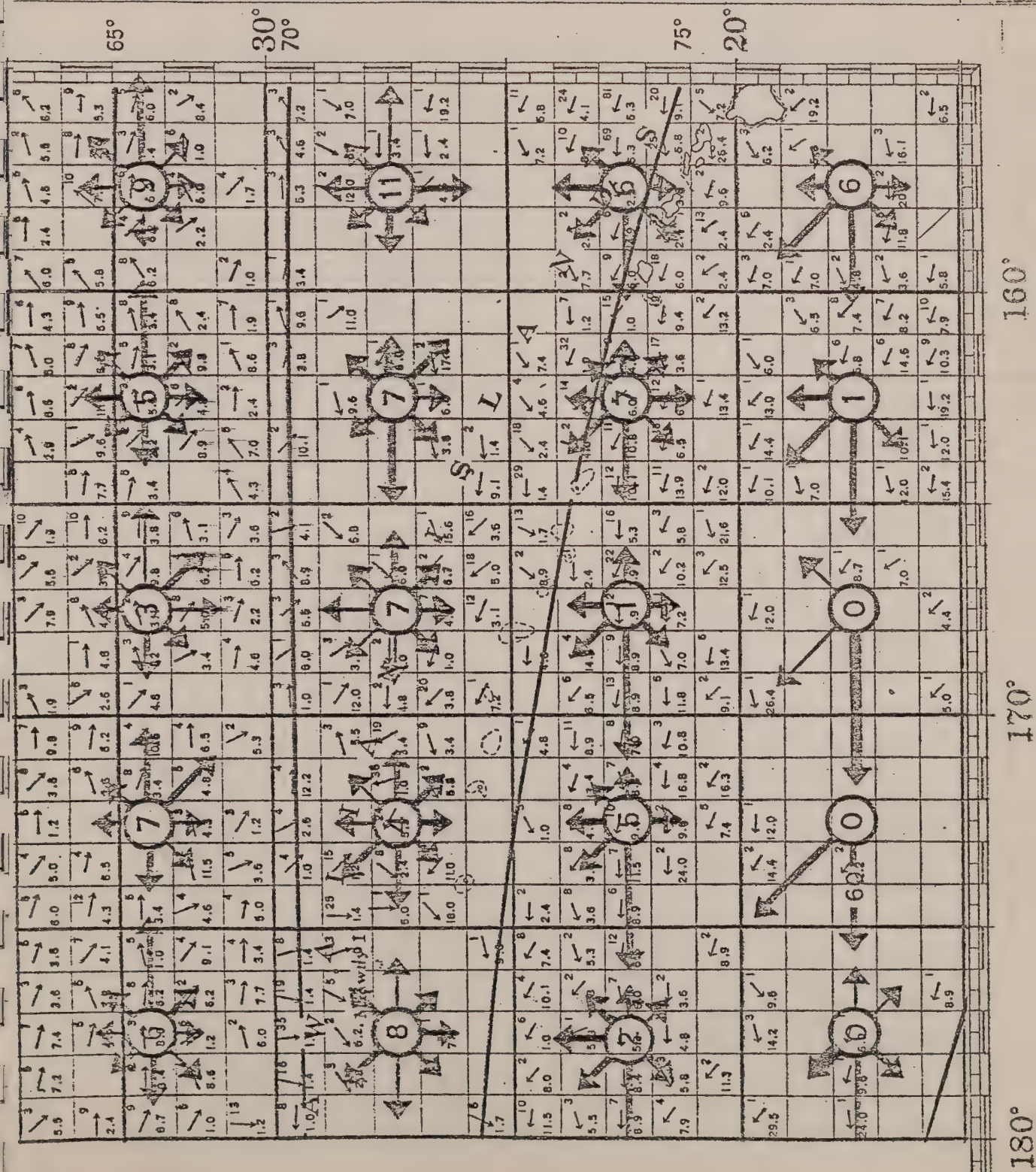


Figure 3lf.--Surface drift vectors for June (U. S. Navy Hydrographic Office 1950).

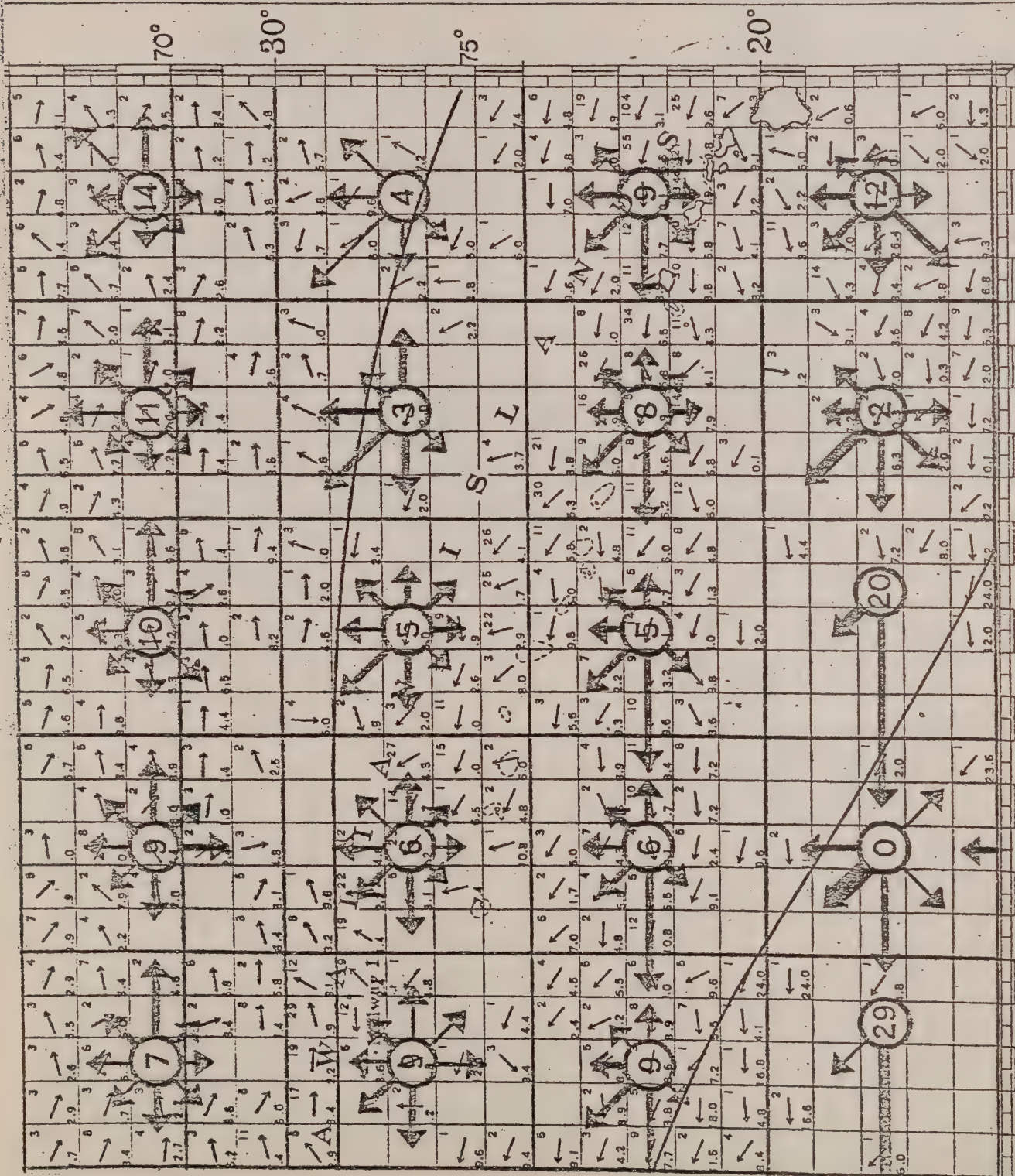


Figure 3lg.—Surface drift vectors for July (U. S. Navy Hydrographic Office 1950).

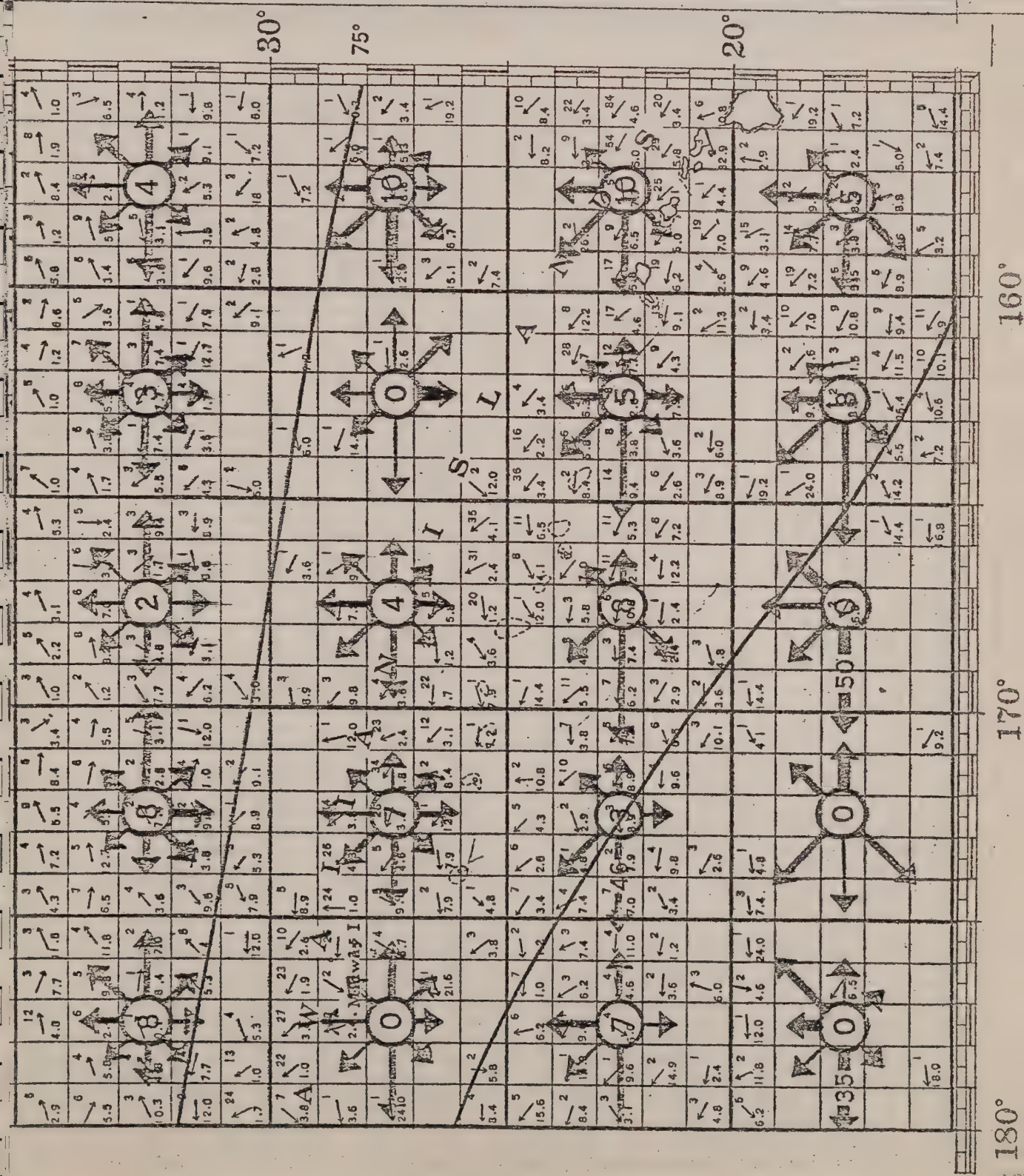


Figure 3lh.—Surface drift vectors for August (U. S. Navy Hydrographic Office 1950).

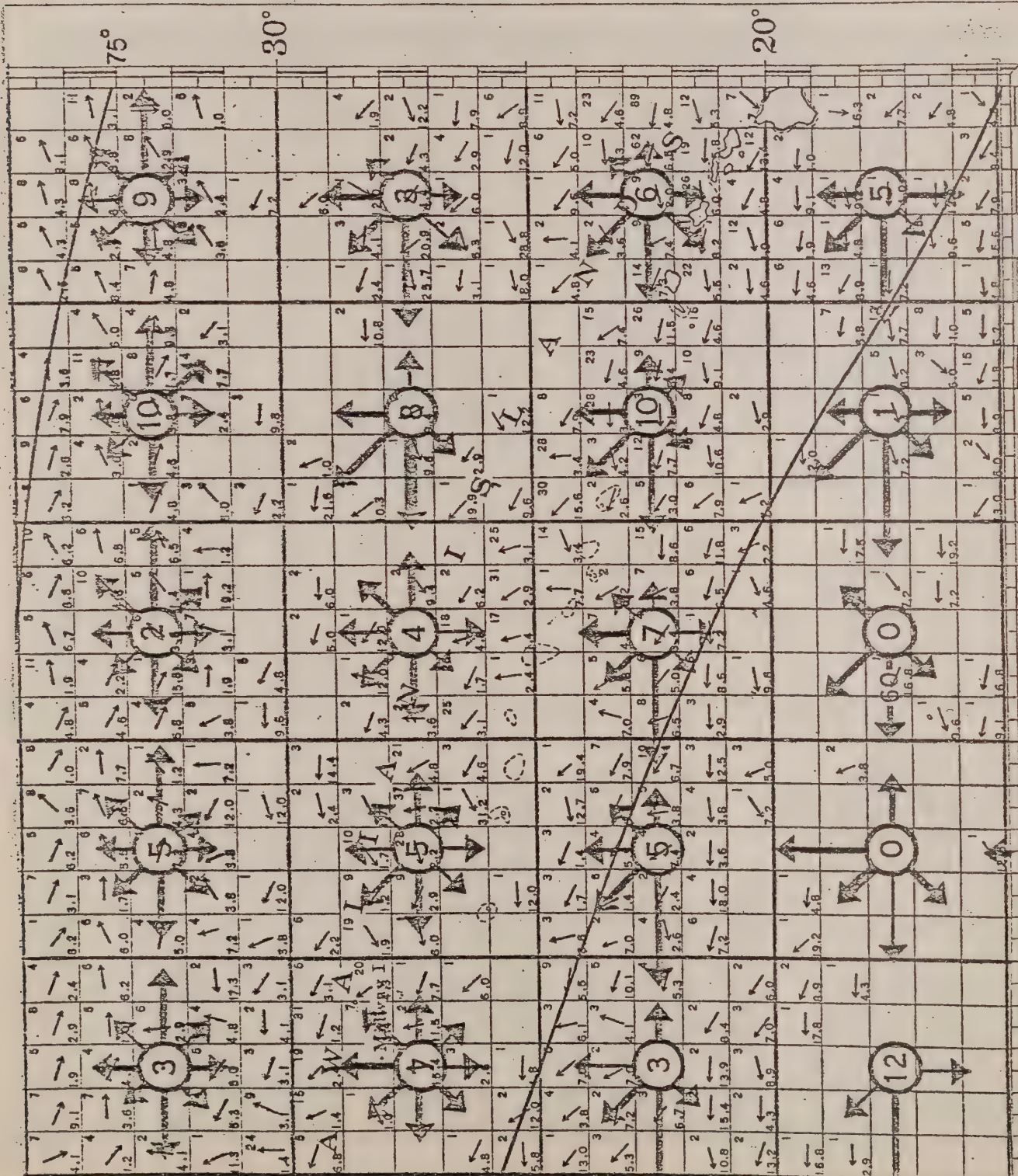


Figure 3li.—Surface drift vectors for September (U. S. Navy Hydrographic Office 1950).

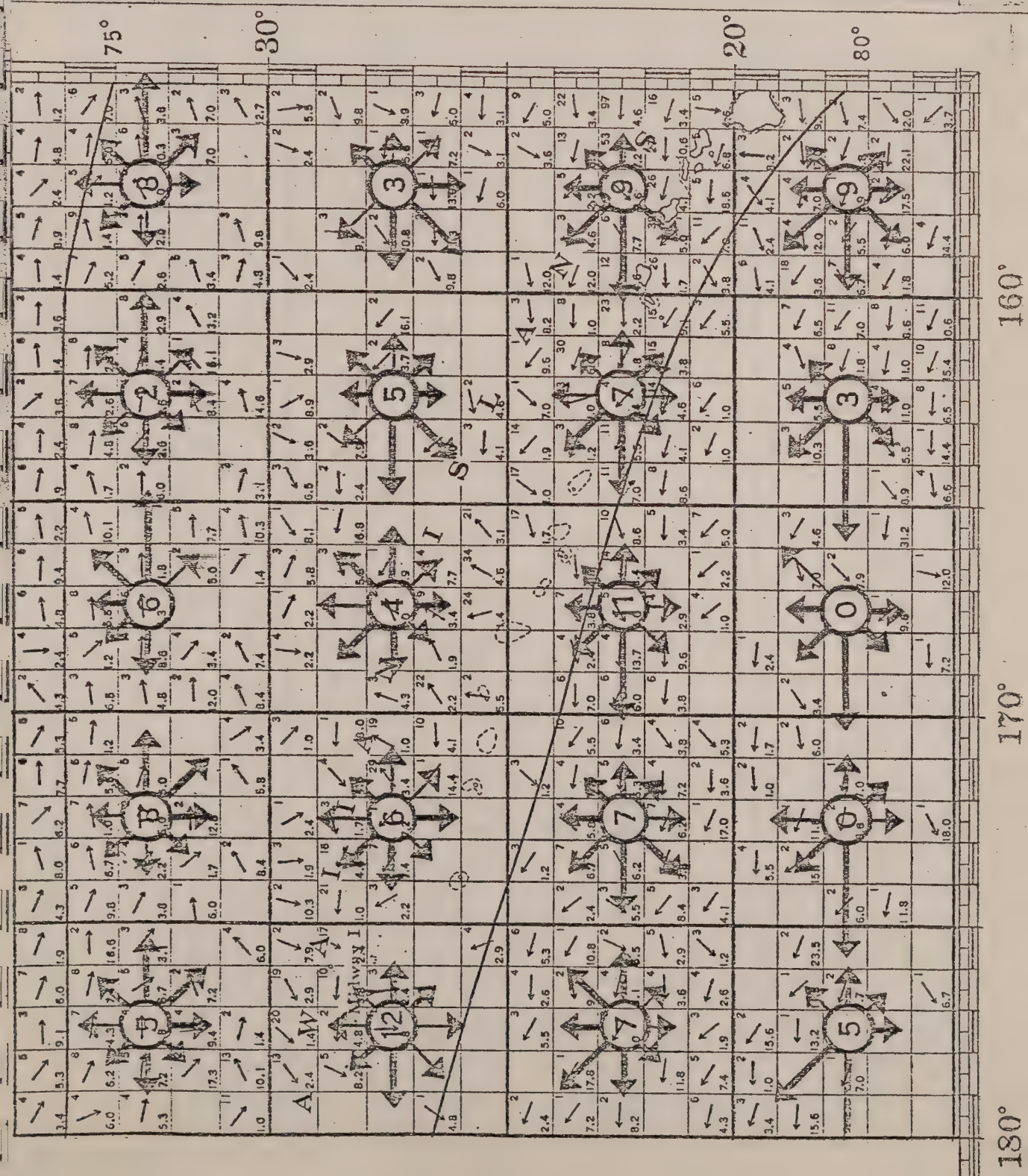


Figure 3lj.—Surface drift vectors for October (U. S. Navy Hydrographic Office 1950).

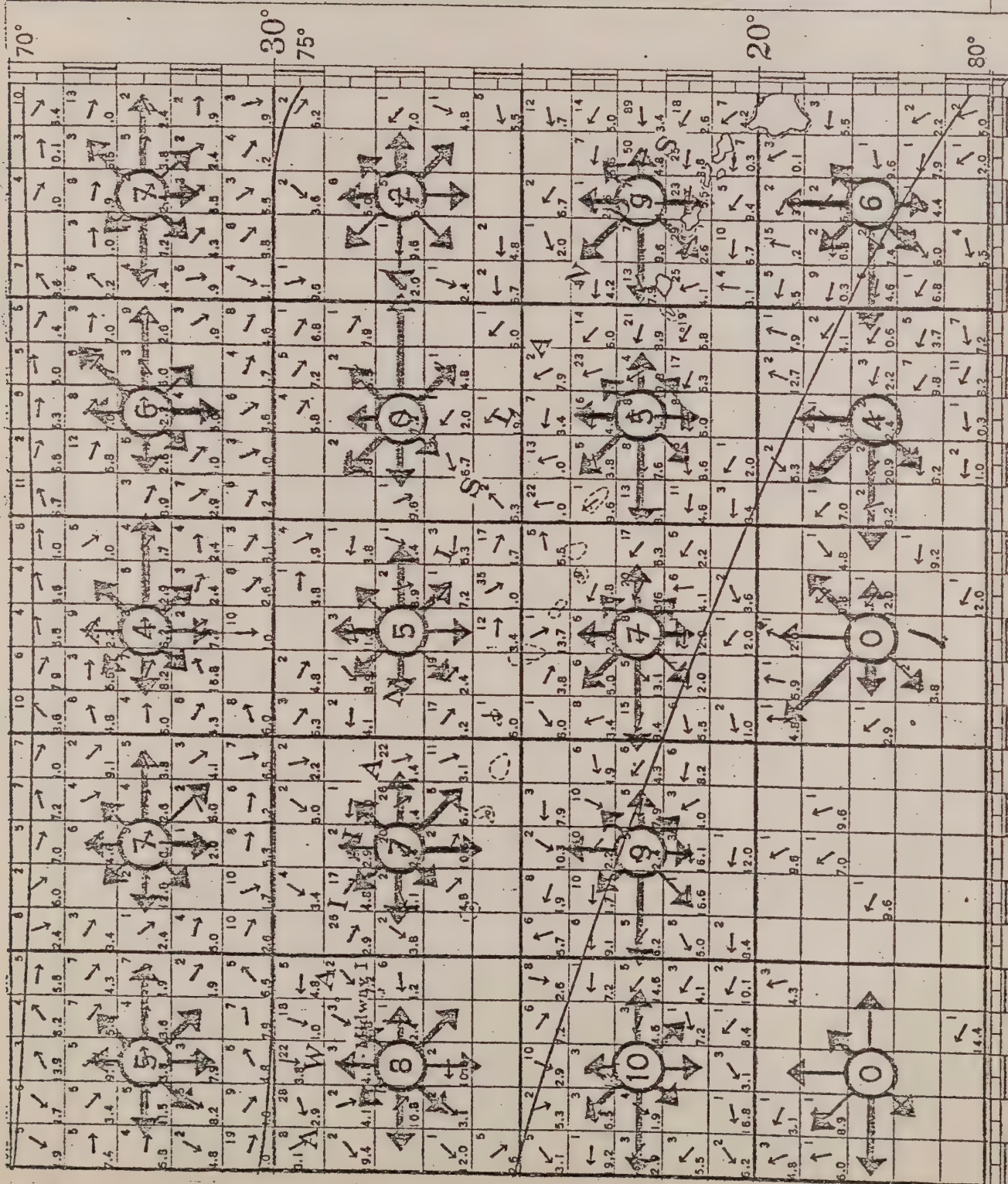


Figure 31k.—Surface drift vectors for November (U. S. Navy Hydrographic Office 1950).

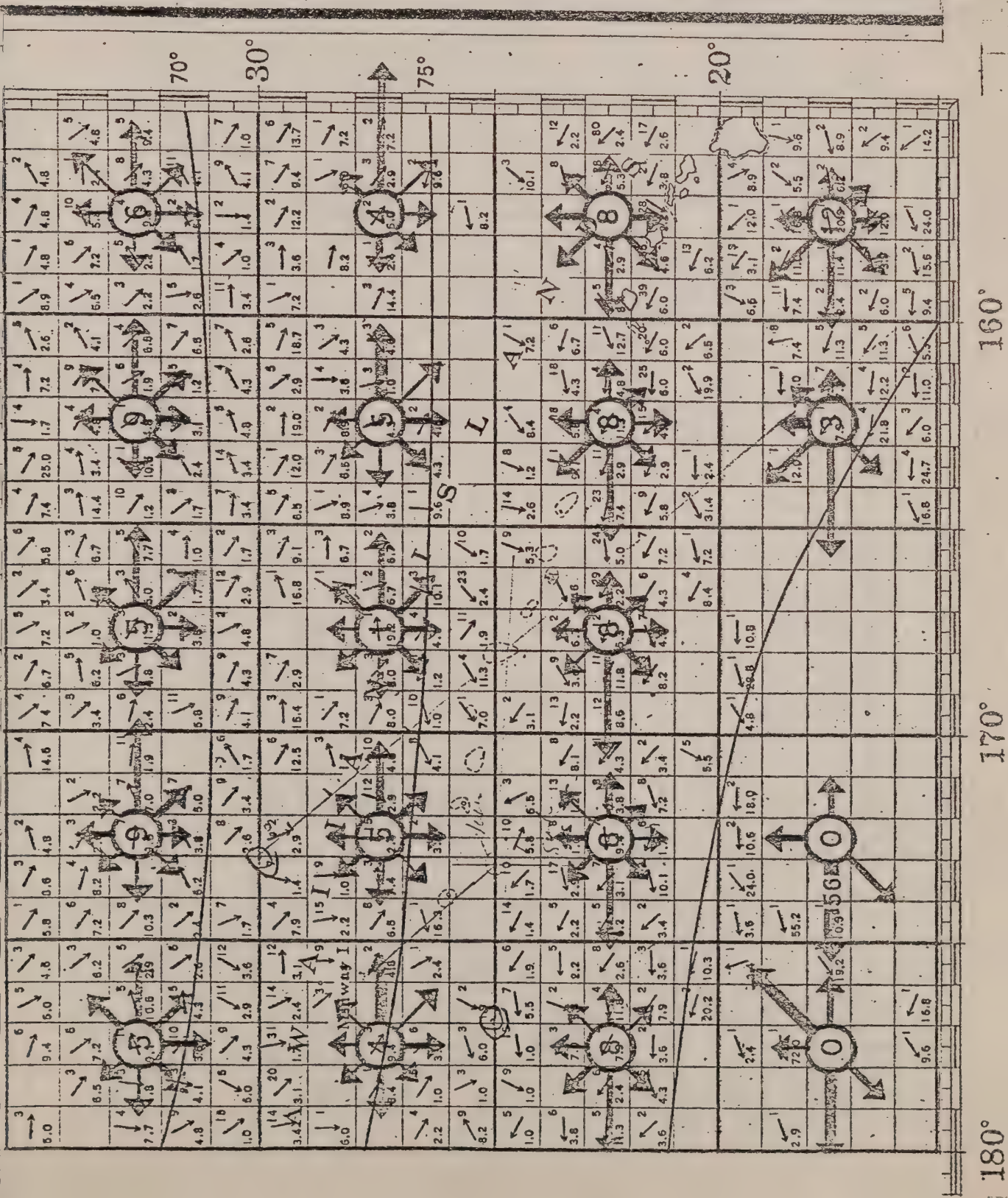


Figure 310.--Surface drift vectors for December (U. S. Navy Hydrographic Office 1950).

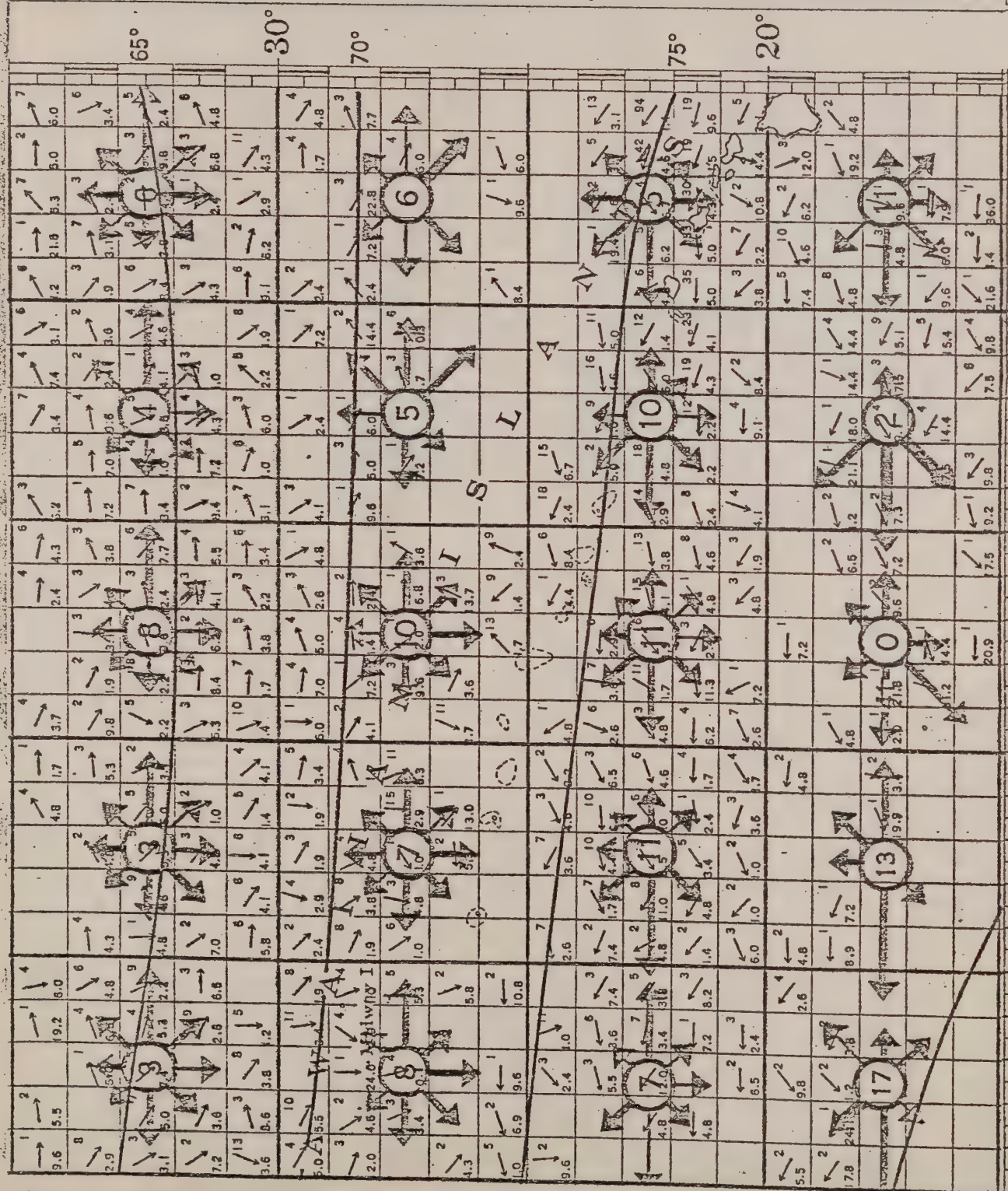




Figure 32a. Bathymetric features in lat 17°-23° N, long 170° E-180°

(Scripps Institution of Oceanography 1971).

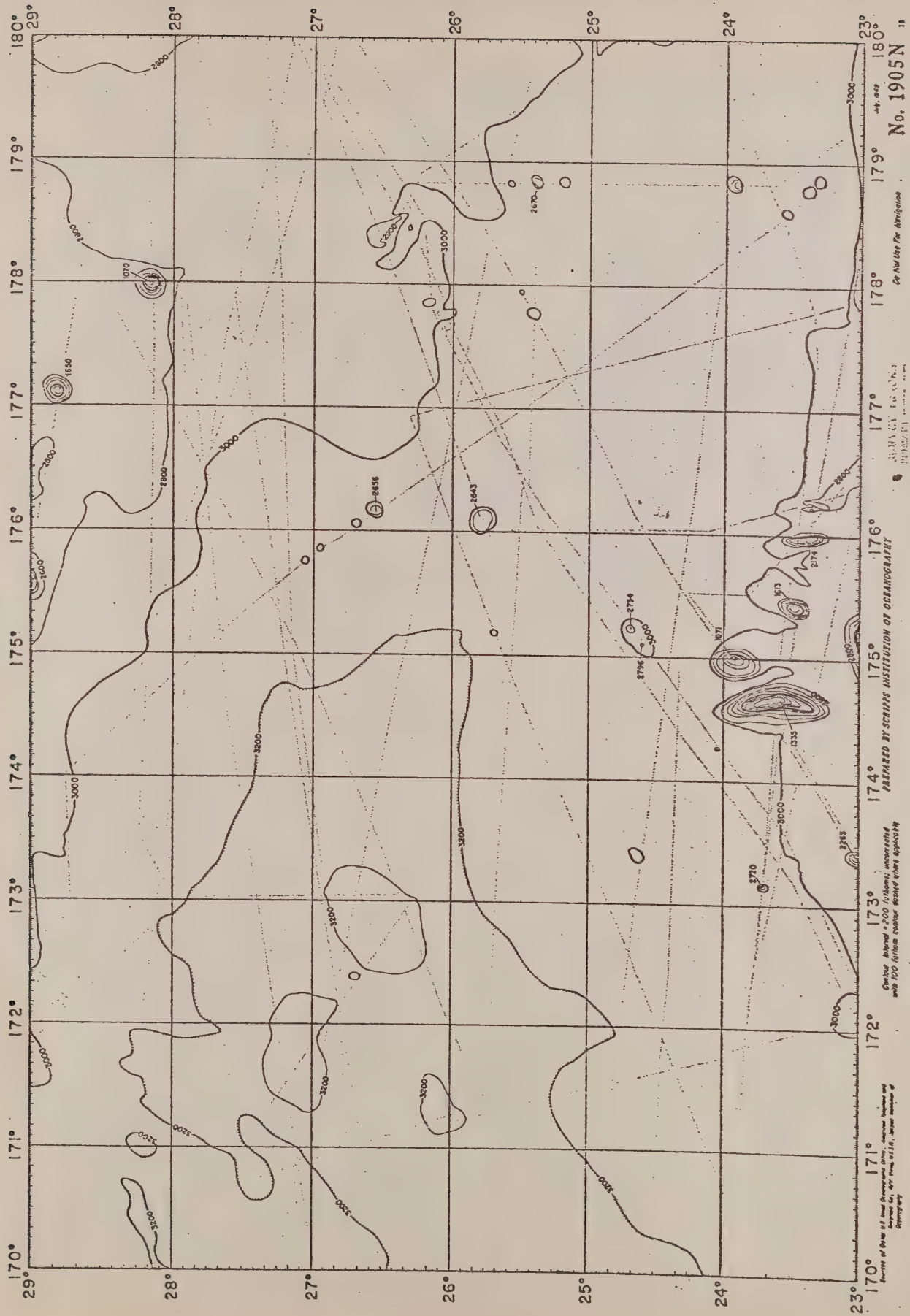


Figure 32b. Bathymetric features in lat 23°-29° N, long 170° E-180°.

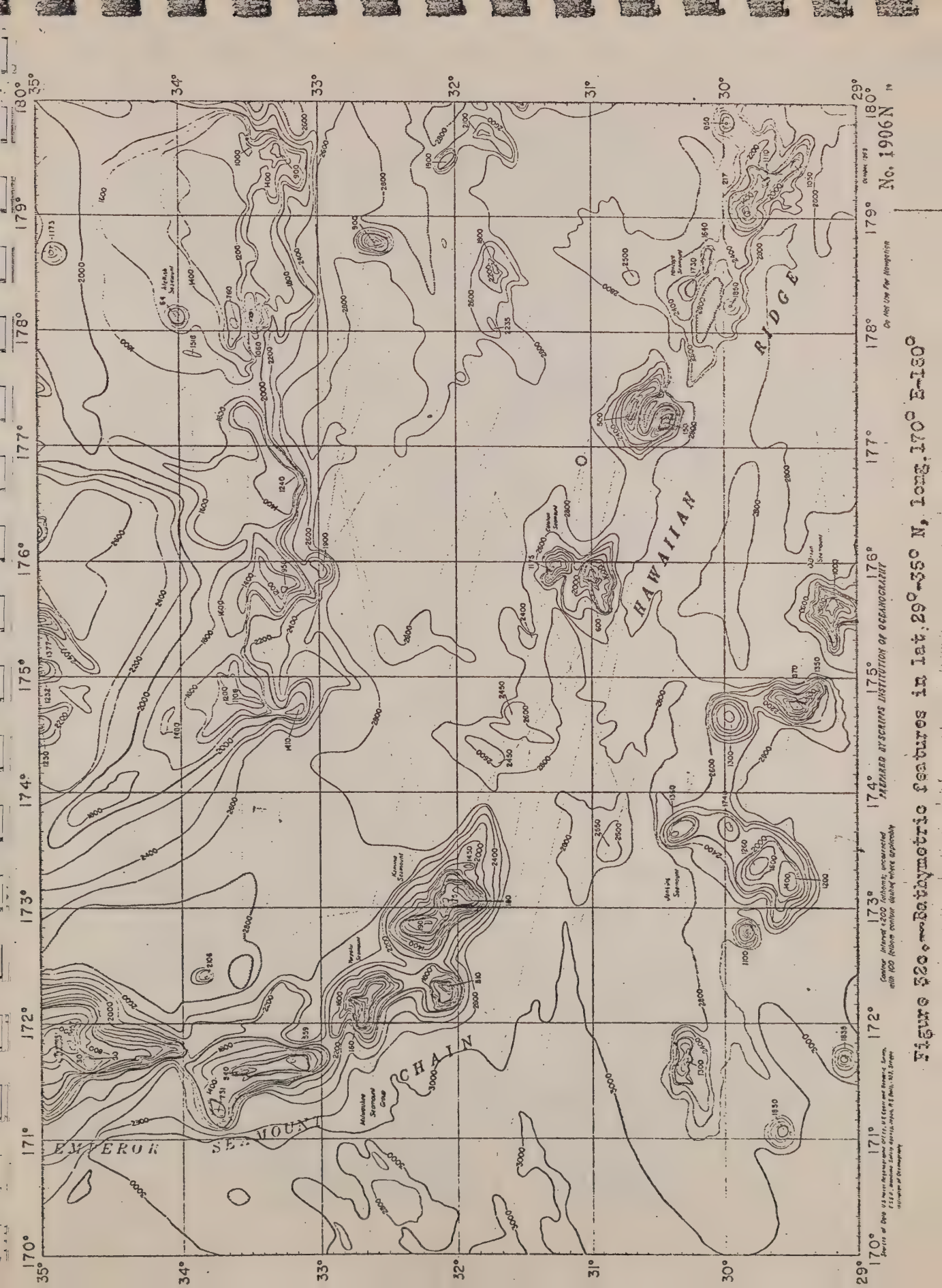


Figure 320. Bathymetric features in lat. 29°-35° N, long. 170° E-180°

170° 171° 172° 173° 174° 175° 176° 177° 178° 179° 180°

29° 30° 31° 32° 33° 34° 35°

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170° 171° 172° 173° 174° 175° 176° 177° 178° 179° 180°

29° 30° 31° 32° 33° 34° 35°

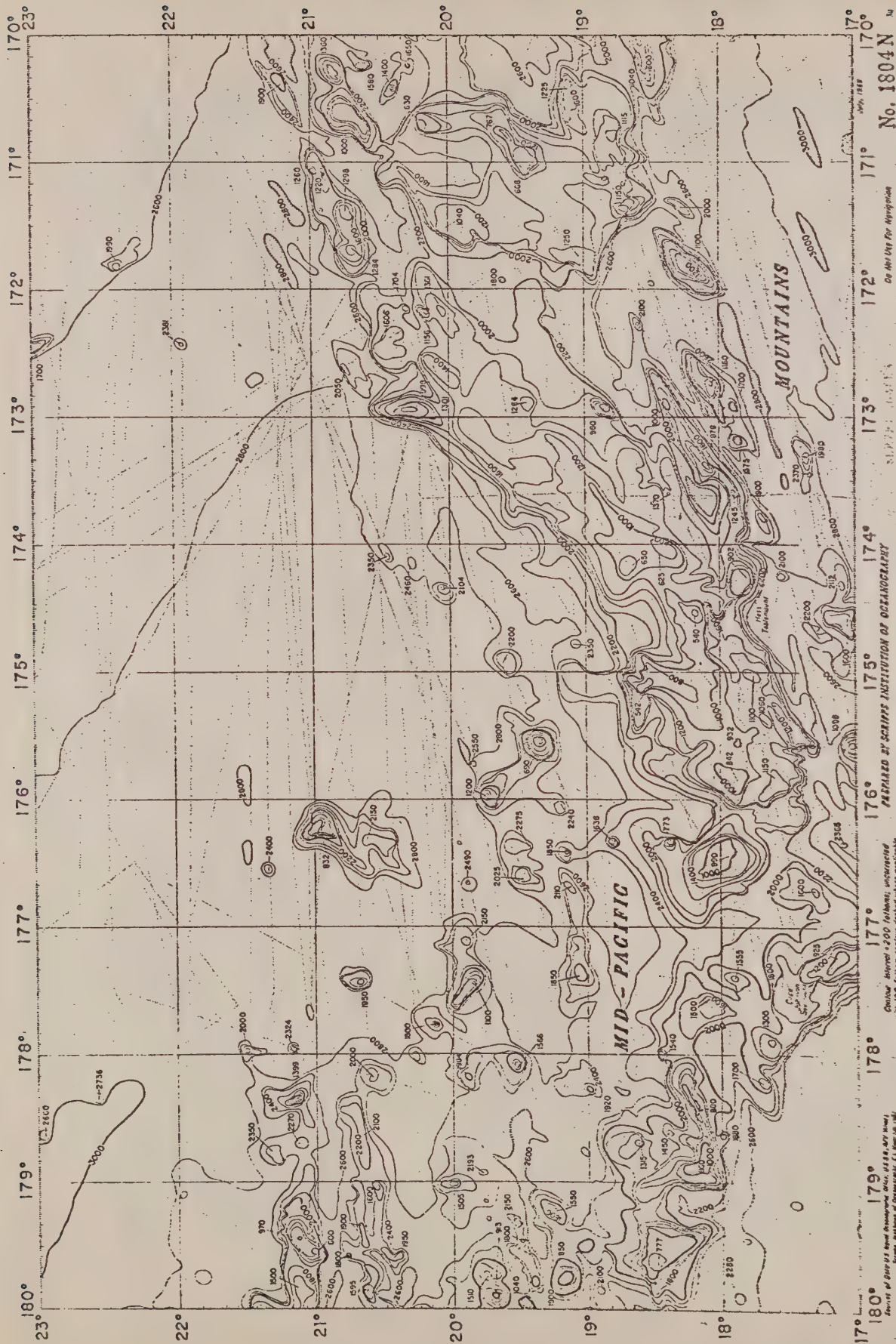


Figure 32d. Bathymetric features in lat. 17°-23° N, long. 170°-180°

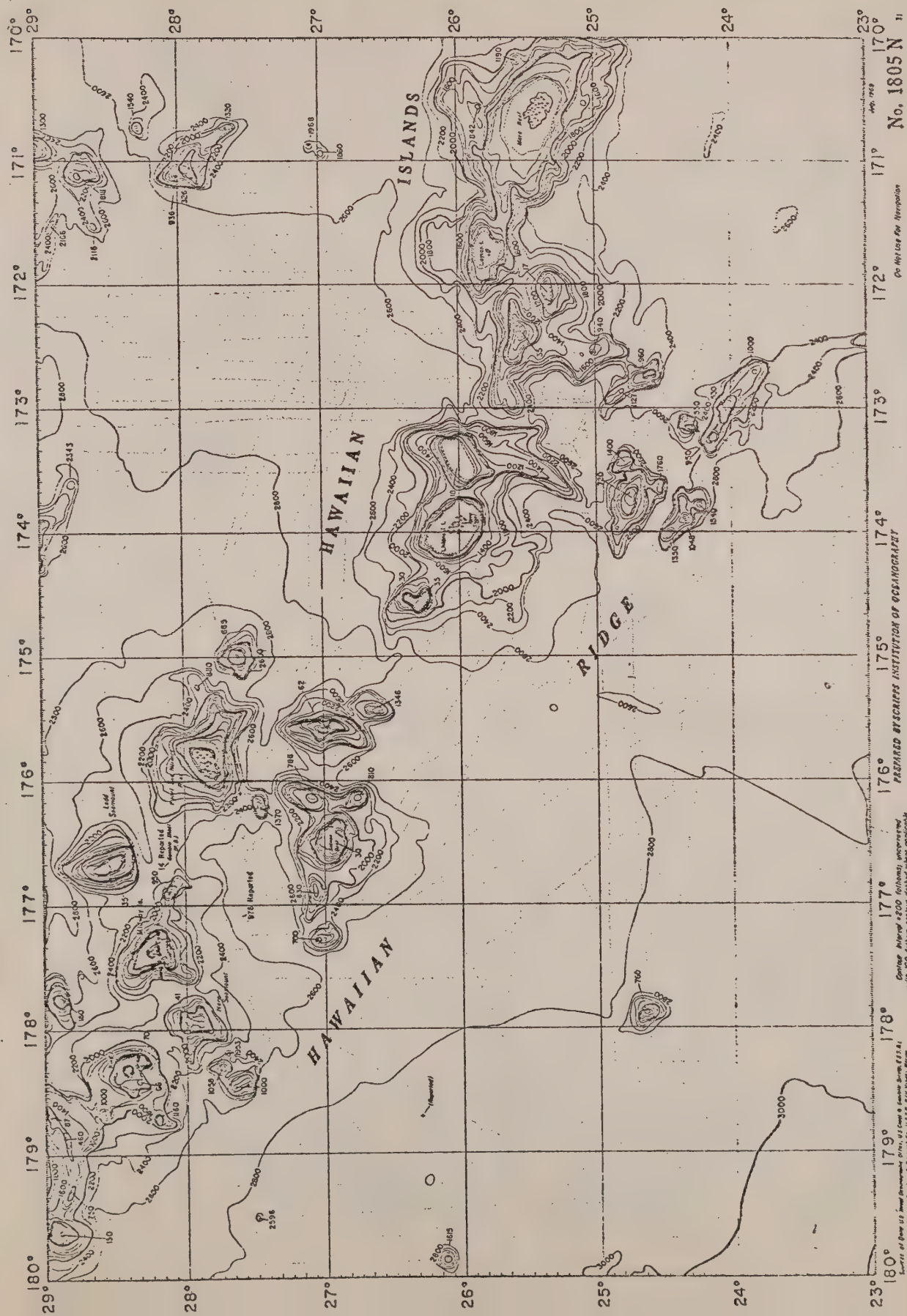
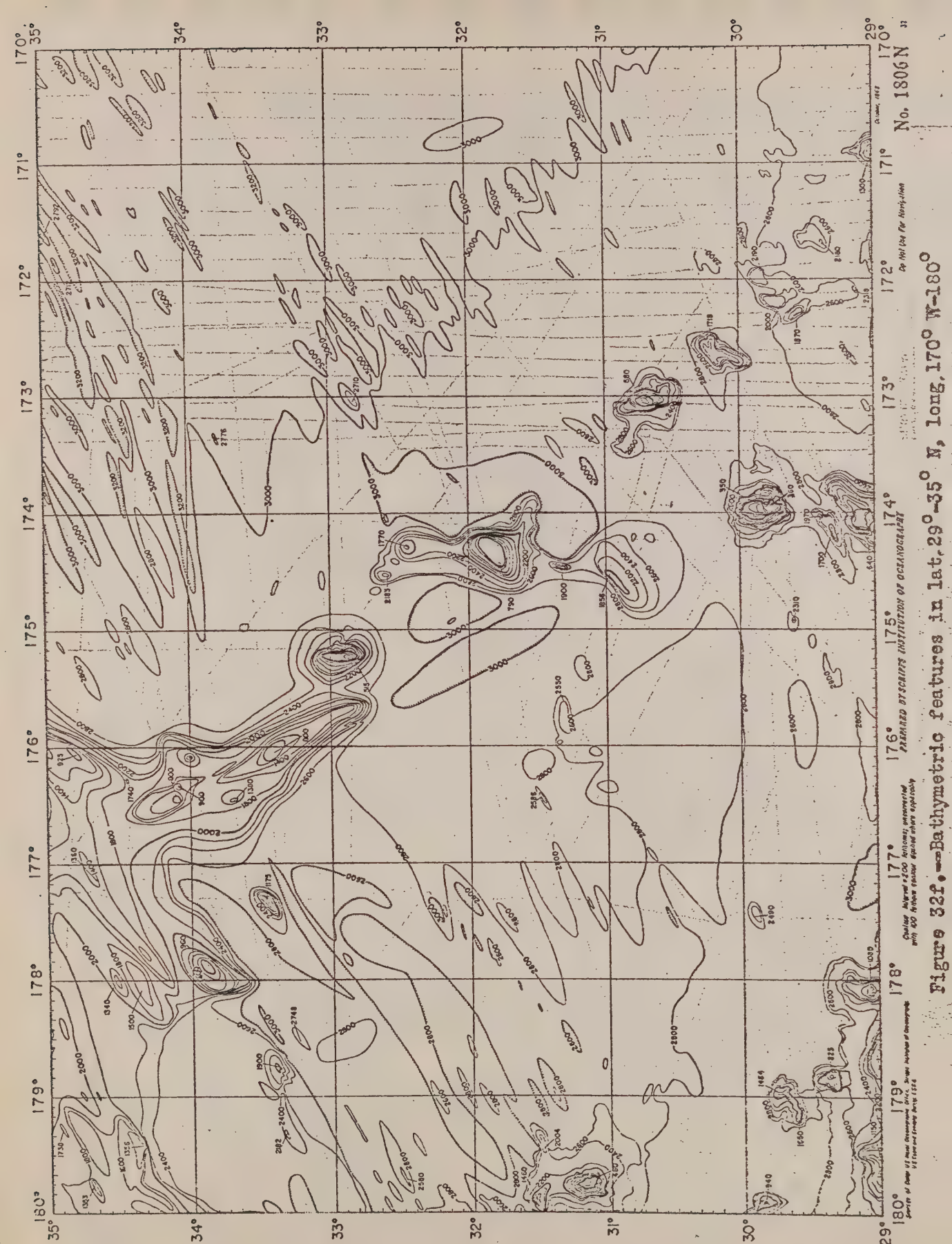
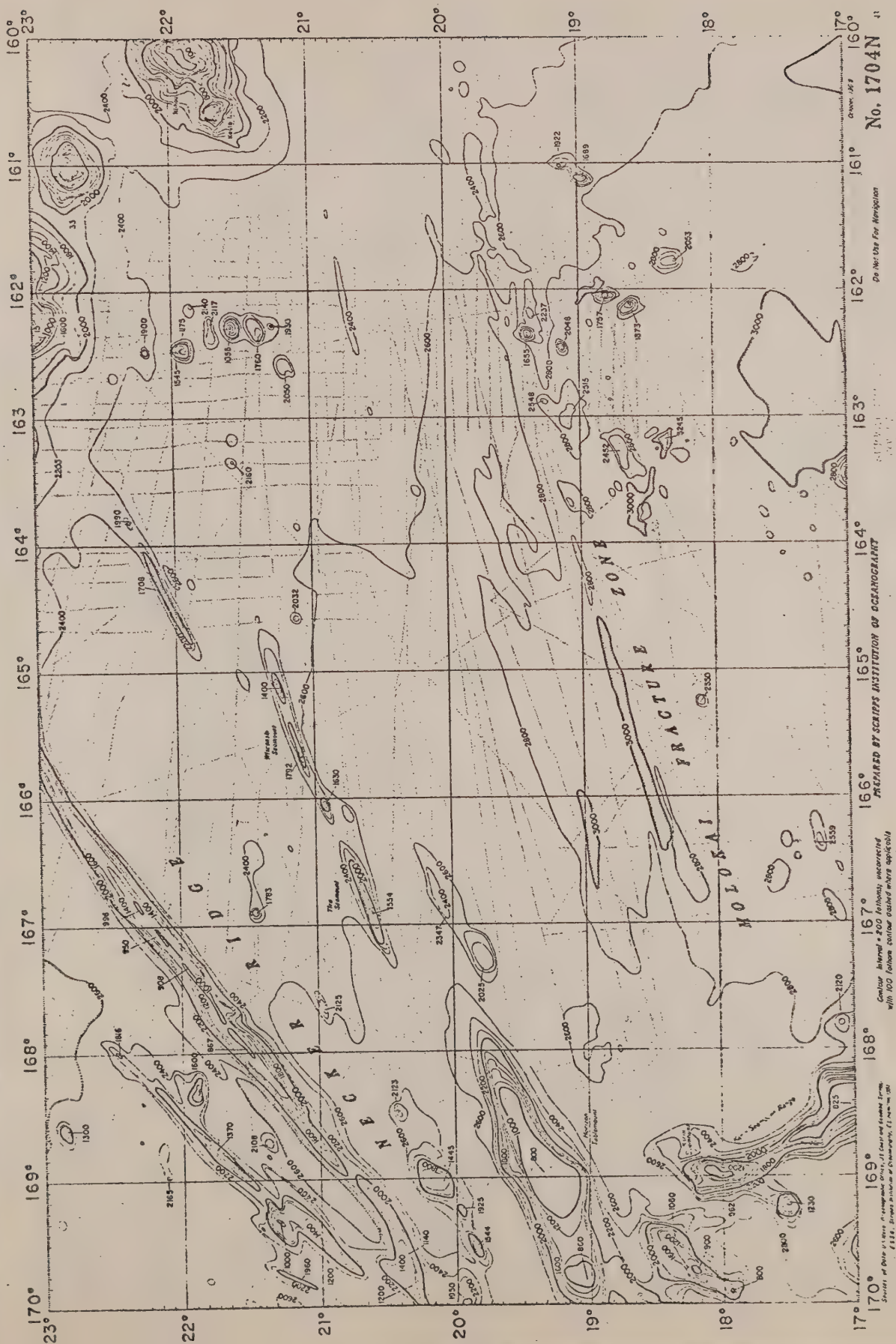


Figure 32e.—Bathymetric features in lat. 23°-29° N, long. 170° W-180°

(Scripps Institution of Oceanography 1971)





No. 1704N

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Contour Interval = 200 fathoms, uncorrected
with 100 fathom contour dashed where applicable

Source: U.S. Navy Hydrographic Office, U.S. Coast and Geodetic Survey
1:125,000 Scale, Bathymetric Edition of Chart No. 1704N

Figure 32g. Bathymetric features in lat. 17°-23° N, long. 160°-170° W

(Scripps Institution of Oceanography 1971)

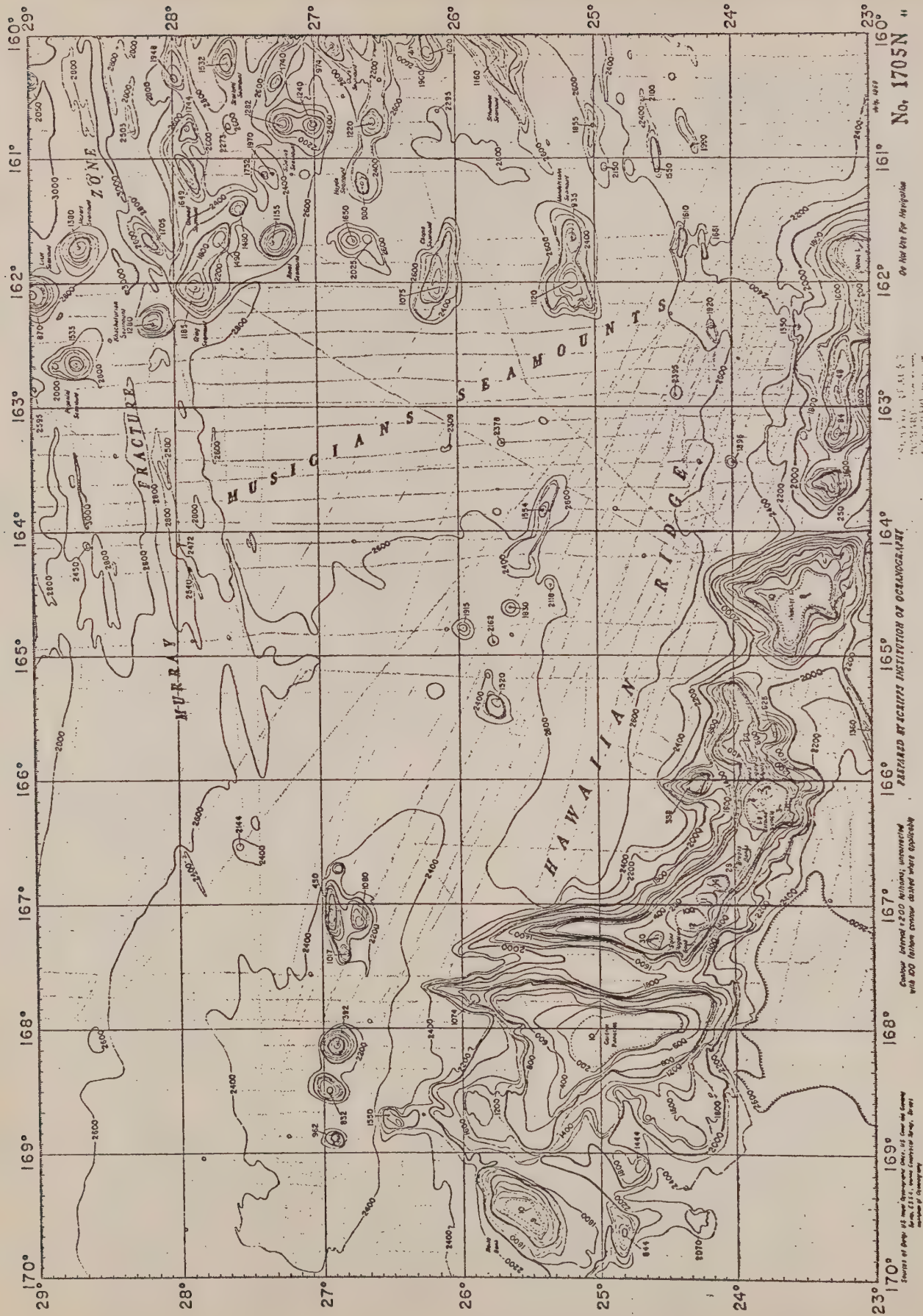


Figure 32h.--Bathymetric features in lat. 23°-29° N, long. 160°-170° W

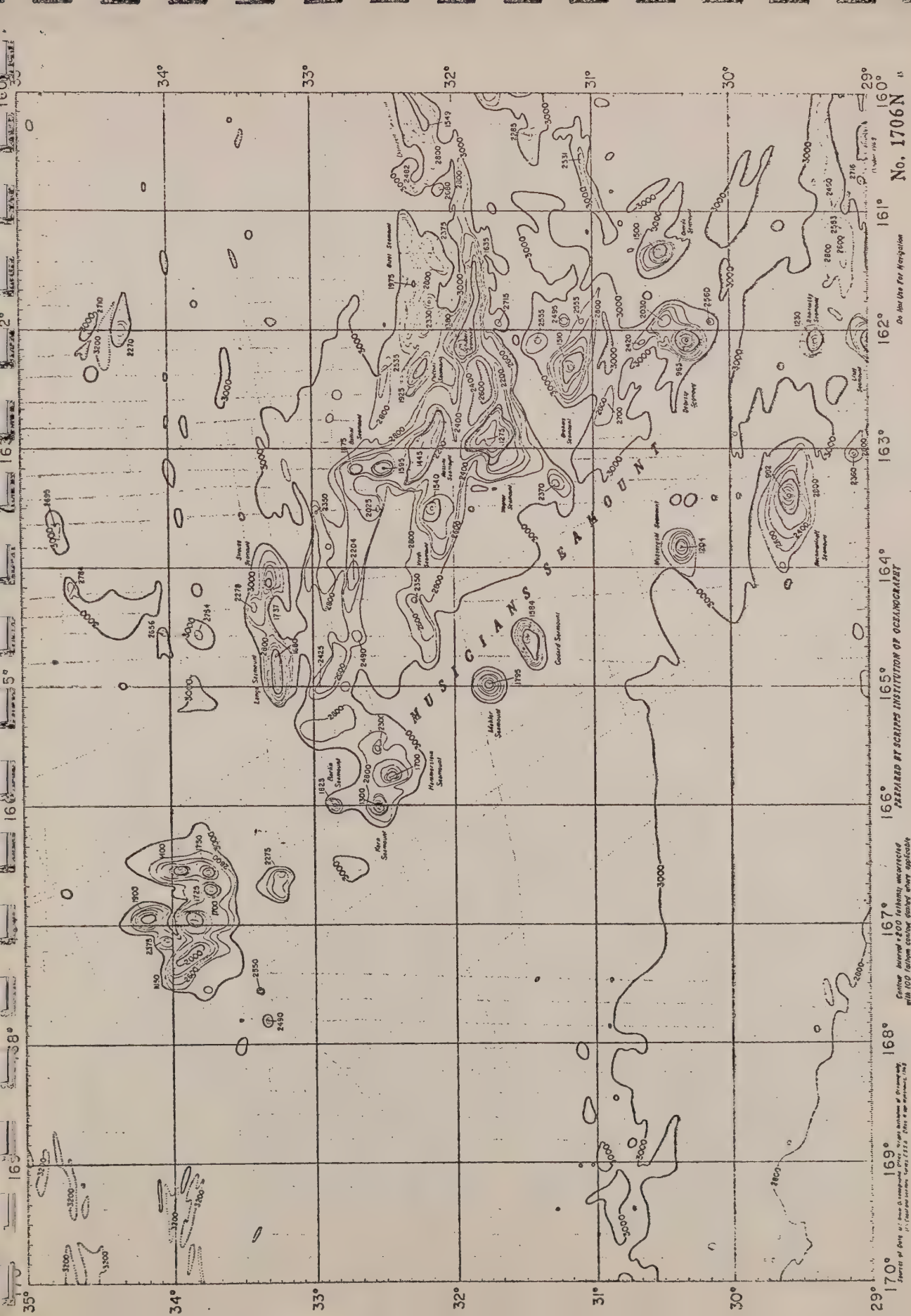


Figure 321.--Bathymetric features in lat. 29°-35° N, long. 160°-170° W

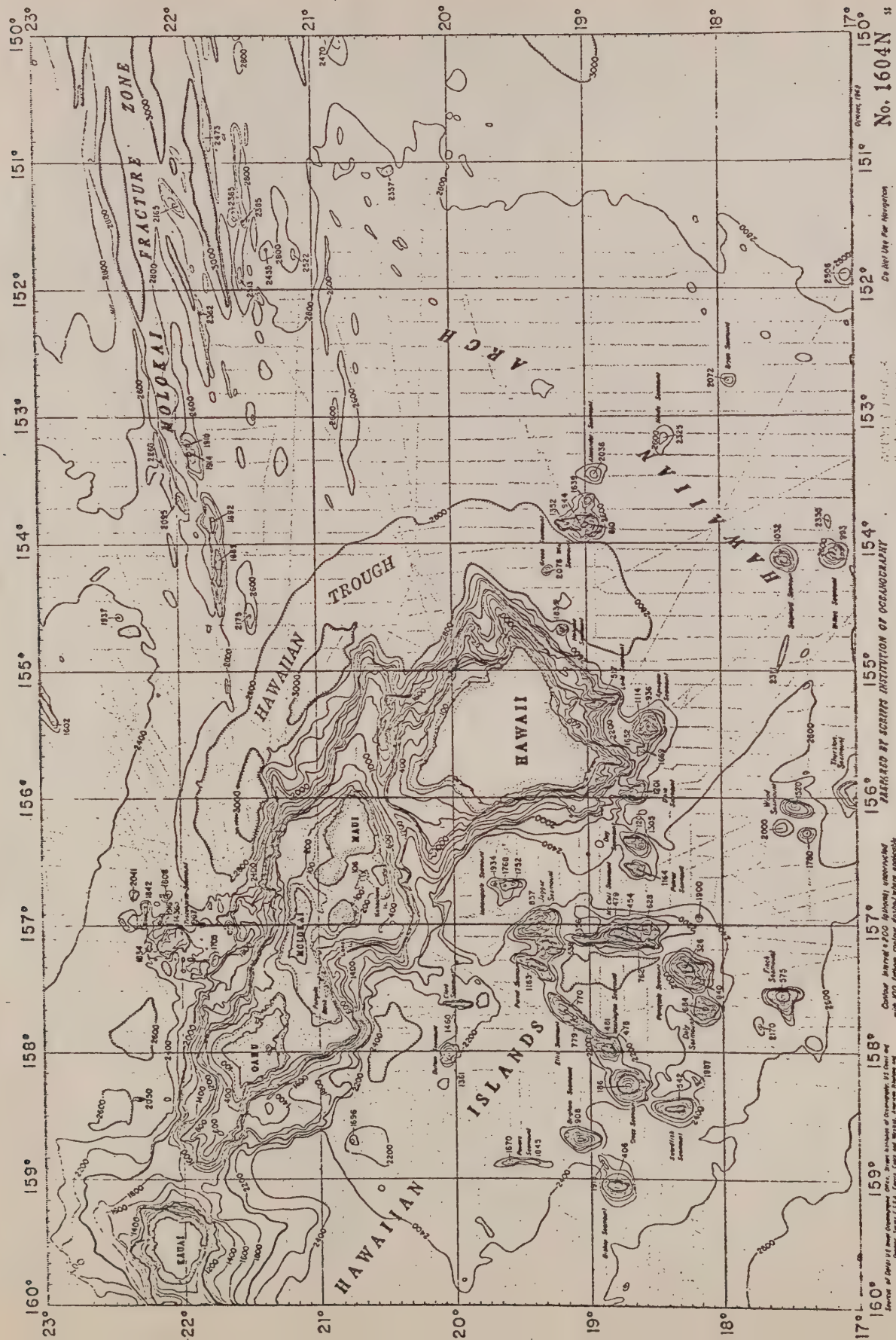


Figure 32j.--Bathymetric features in lat 17°-23° N, long 150°-160° W

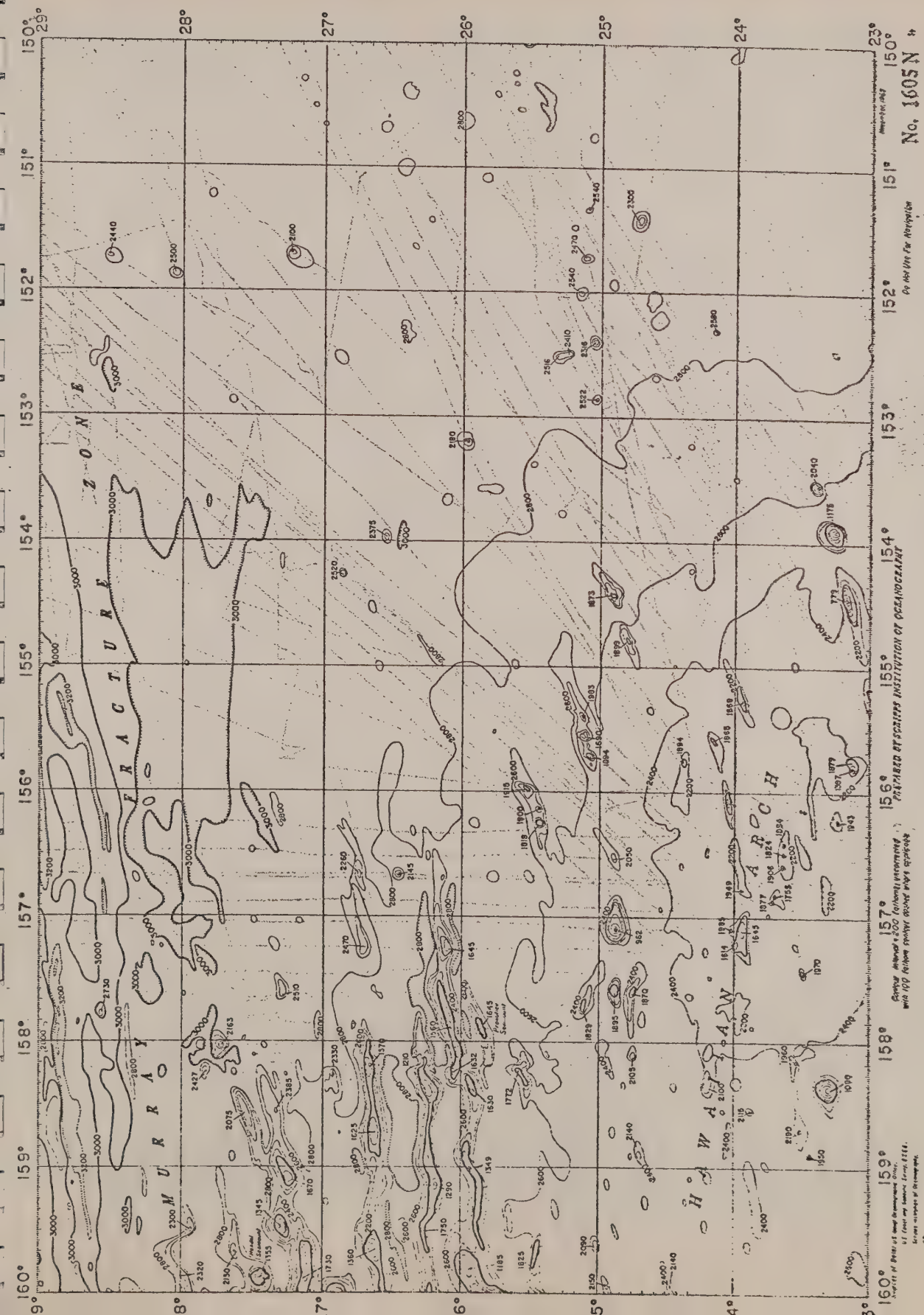


Figure 32k. Bathymetric features in lat 23°-29° N, long 150°-160° W

(Scripps Institution of Oceanography 1971).

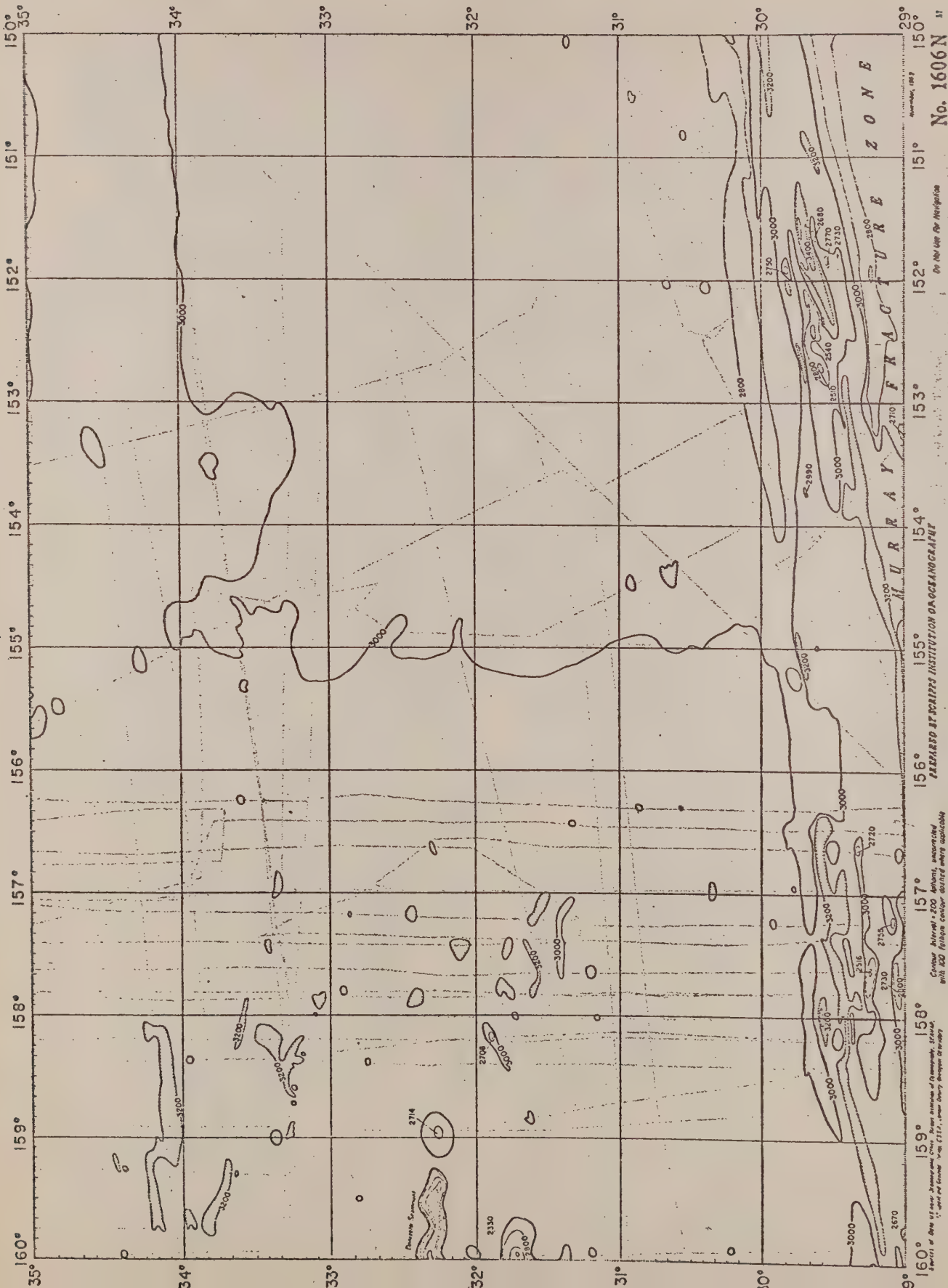


Figure 320. Bathymetric features in lat 29°-35° N. long 150°-160° W

Chart No. 1606N
No. 1606N

By the U.S. Navy Hydrographic Office

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Chart No. 1606N
No. 1606N

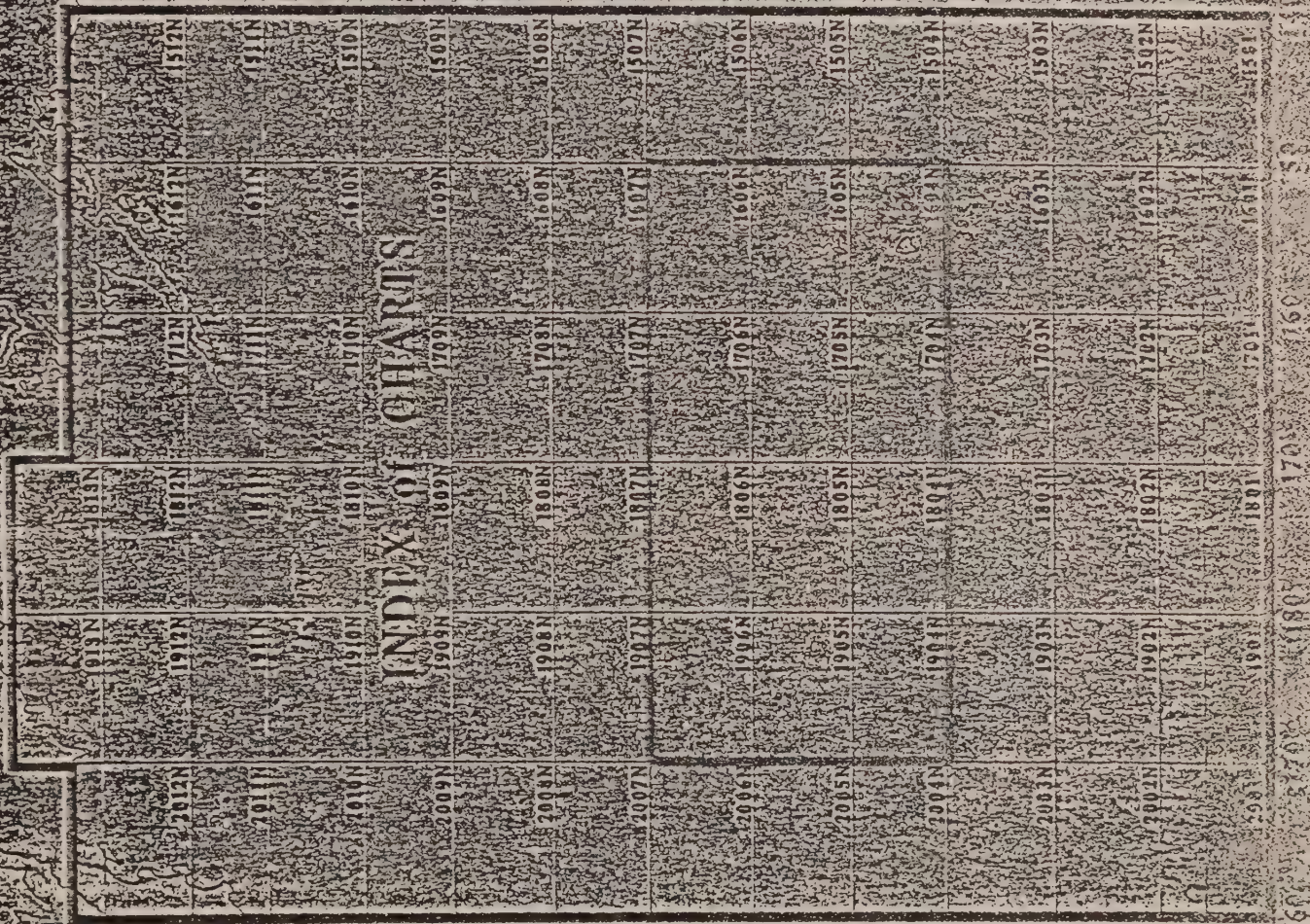


Figure 33.--The locations of the individual bathymetric charts, shown in Figures 32a-32l, in relation to the rest of the northcentral

Reid 1962
Fig. 34

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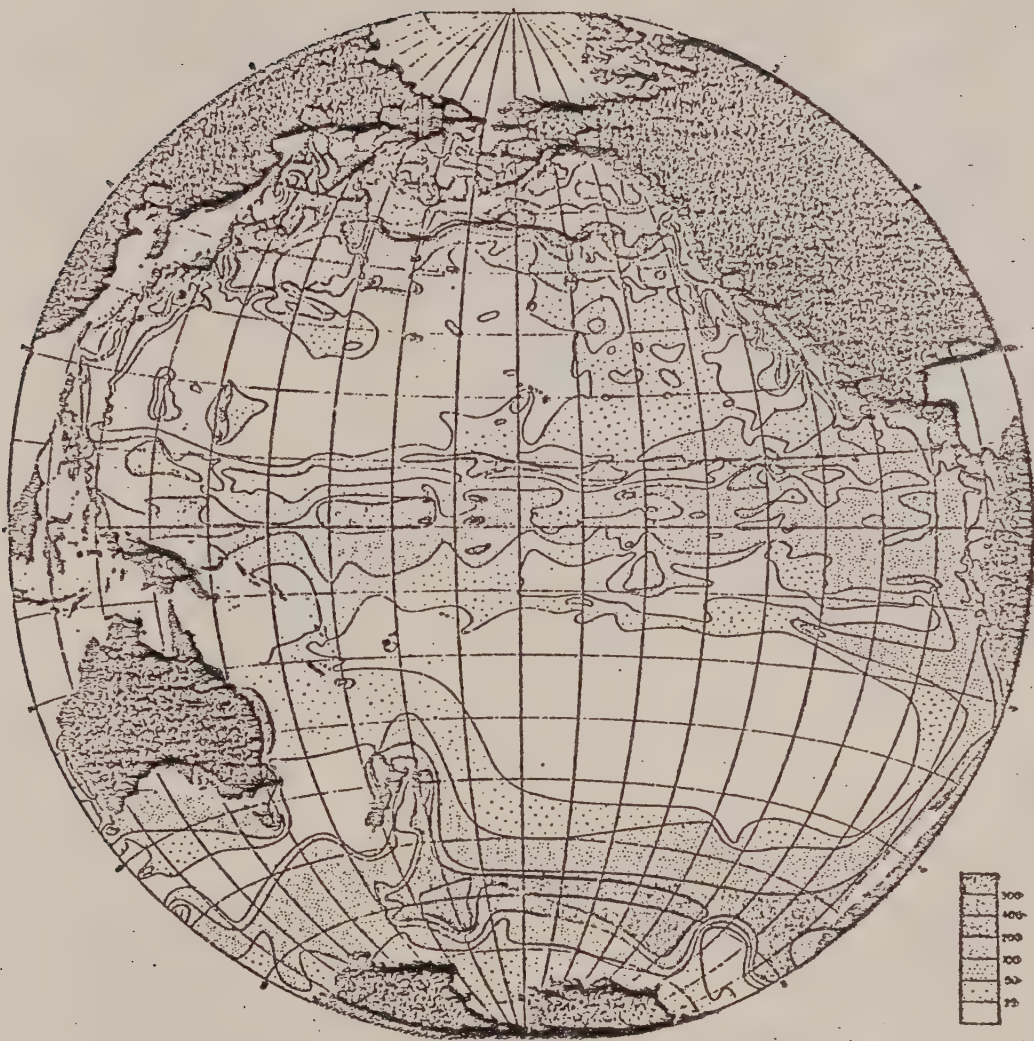


Figure 34.—Distribution of zooplankton volume (parts per 10^9 by volume) in approximately the upper 150 m of the Pacific Ocean, shaded by values (Reid, 1962).

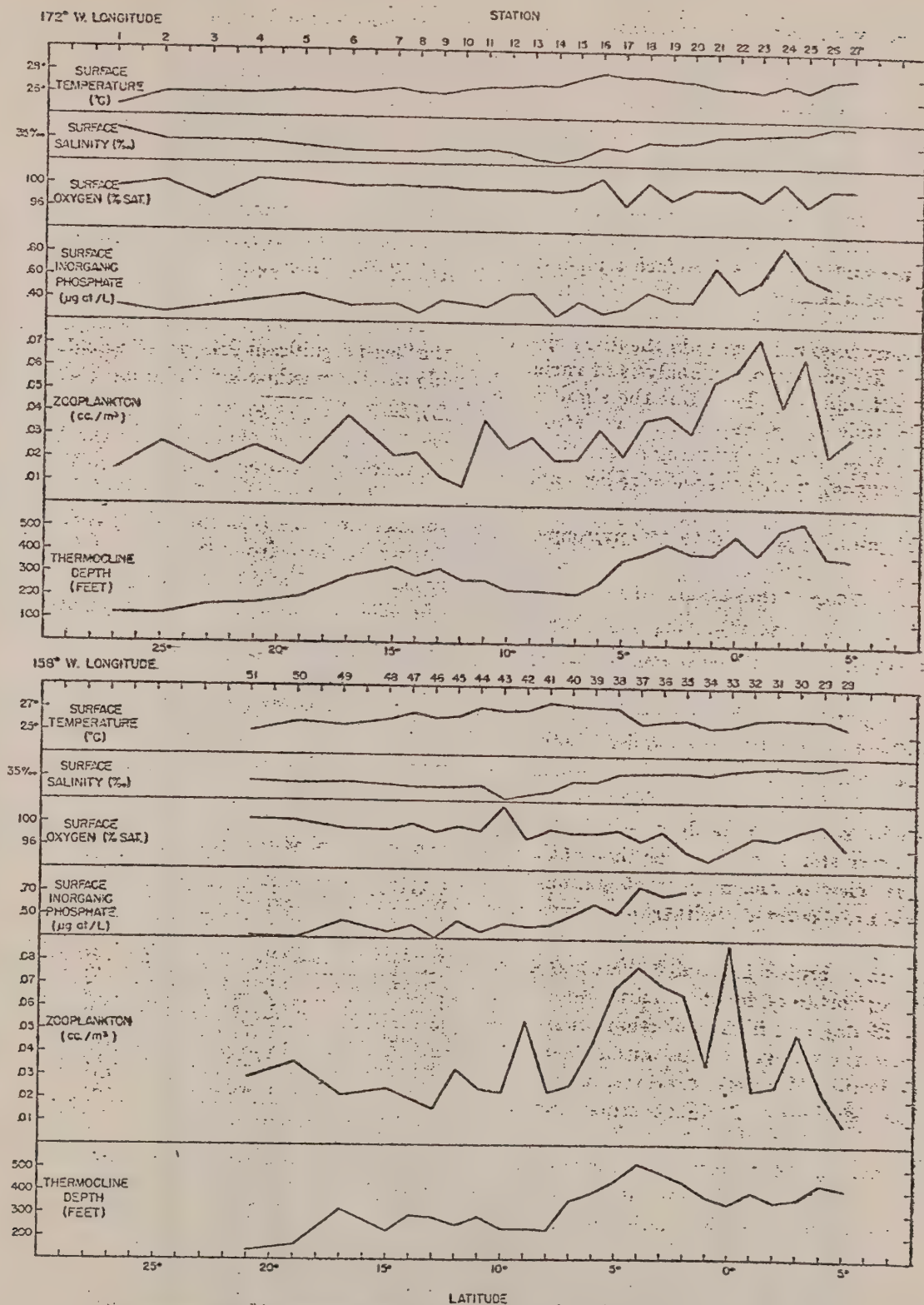


Figure 35.—Variations in temperature, salinity, oxygen, inorganic phosphate, thermocline depth, and zooplankton volume along long 158° and 172° W as found on cruise 5, Hugh M. Smith, June-August 1950. (King and Demond 1953).

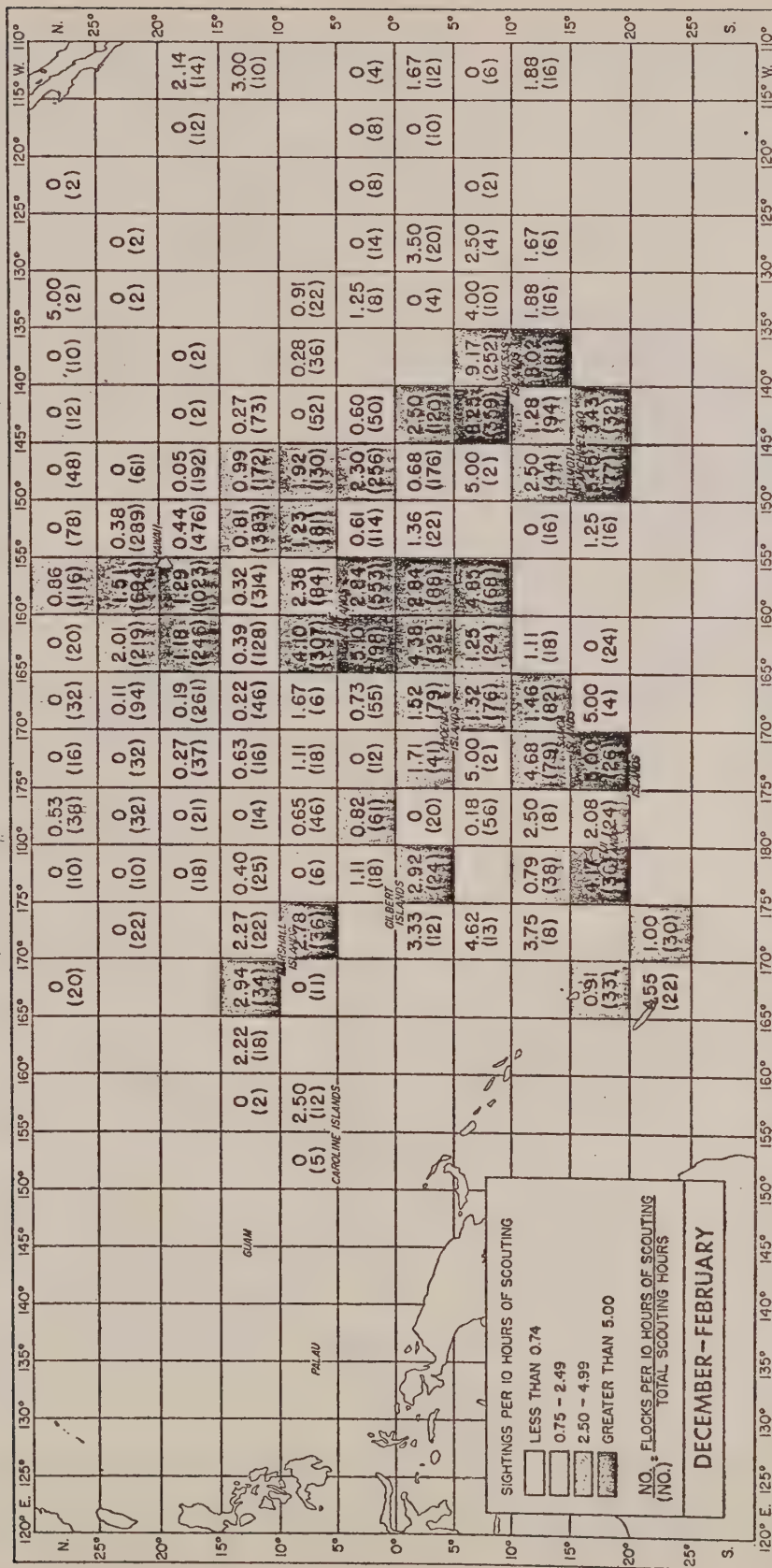


Figure 36a. Bird flock sightings by National Marine Fisheries Service

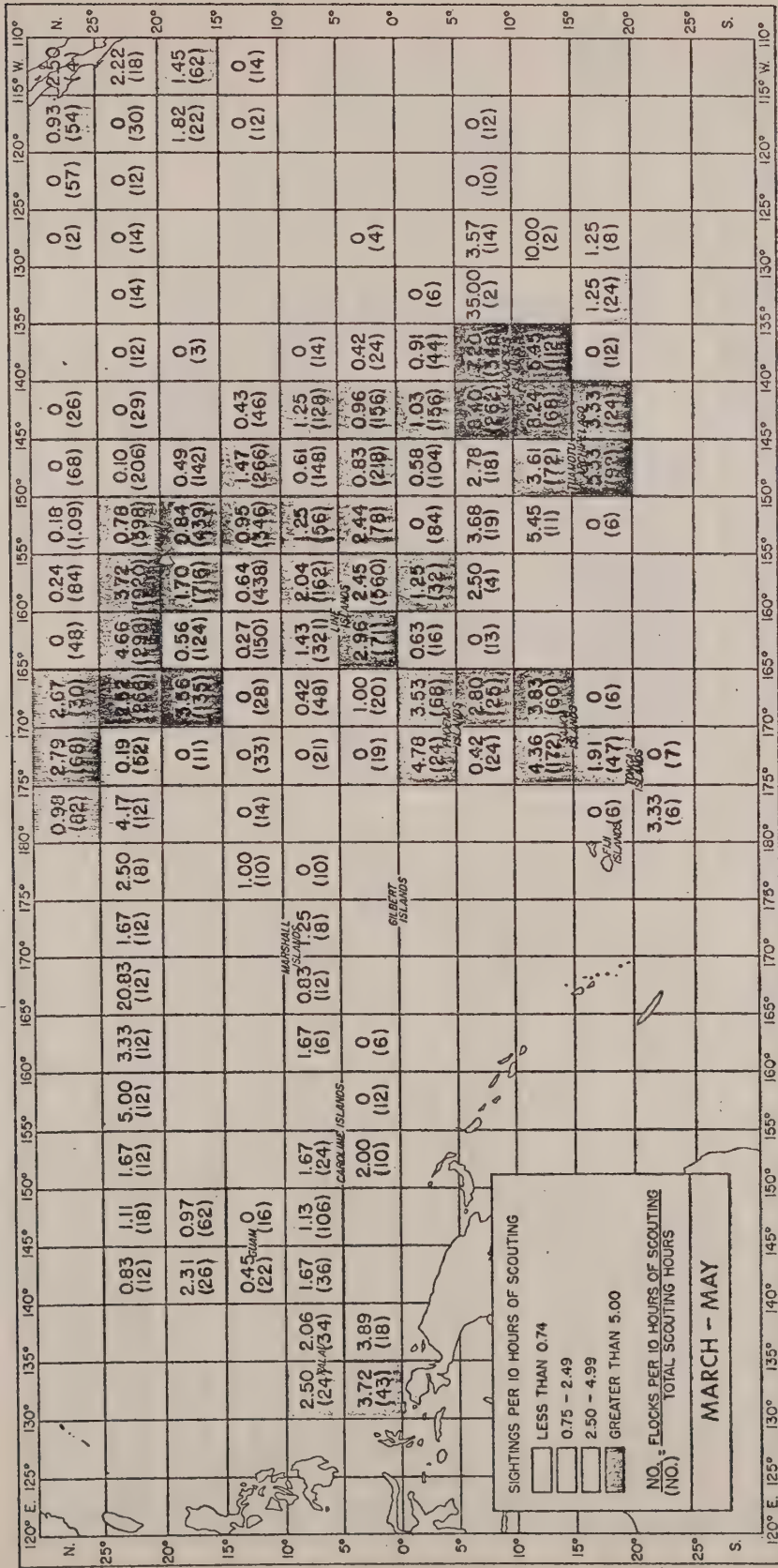


Figure 36b.--Bird flock sightings by National Marine Fisheries Service vessels, March-May 1950-72 (Naughton 3/).

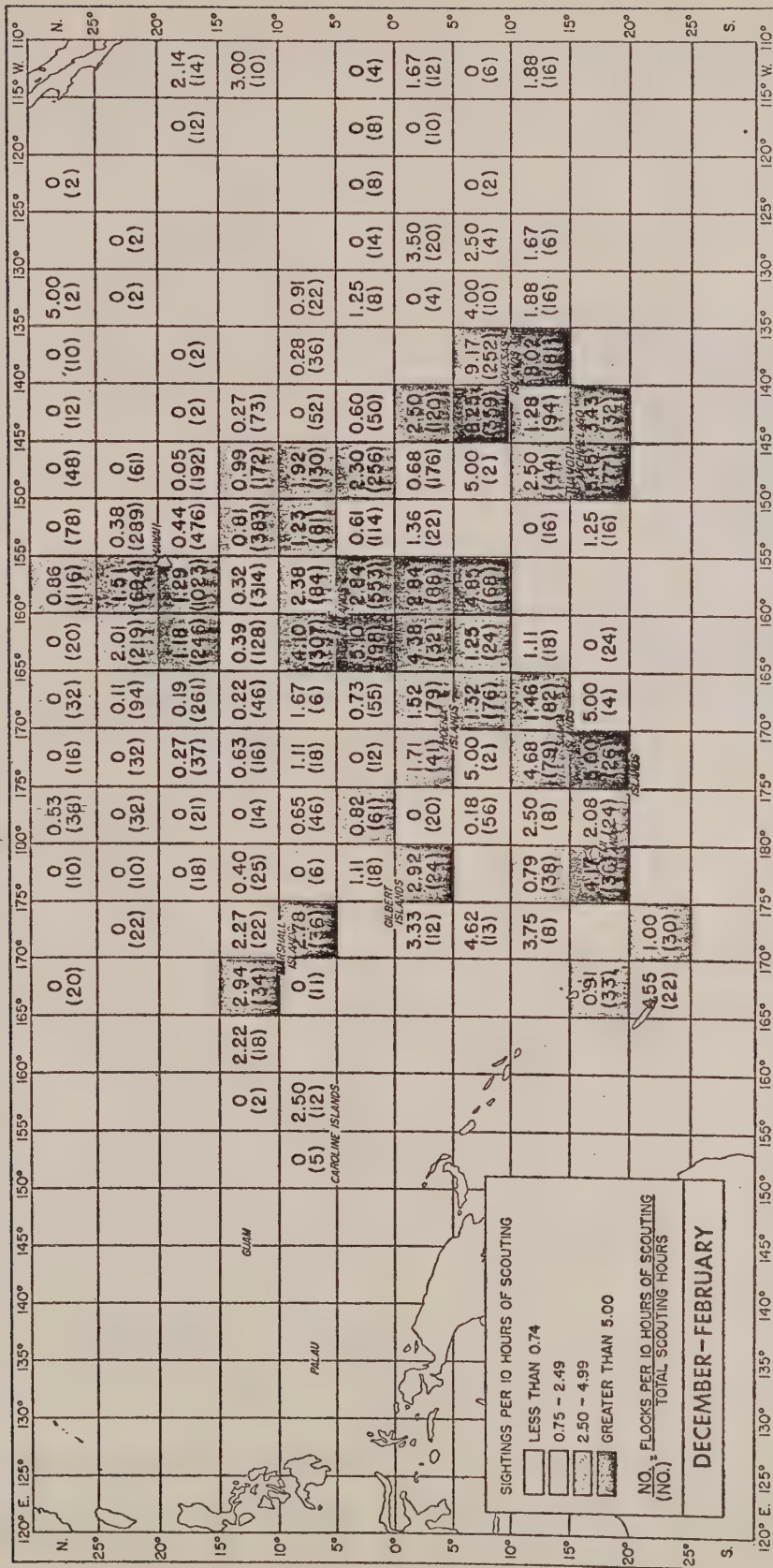


Figure 36a. Bird flock sightings by National Marine Fisheries Service

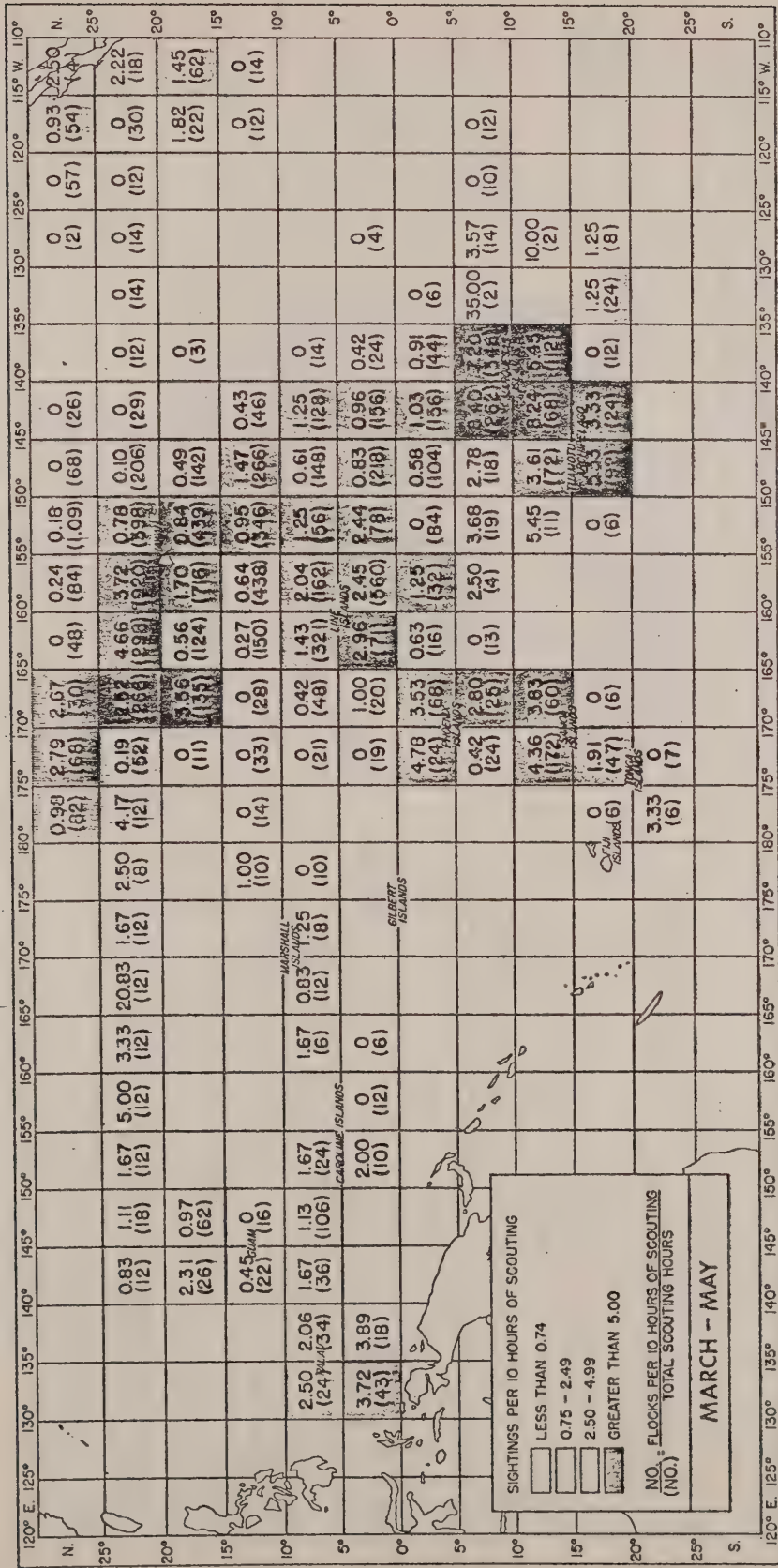


Figure 36b.--Bird flock sightings by National Marine Fisheries Service vessels, March-May 1950-72 (Naughton 3/).

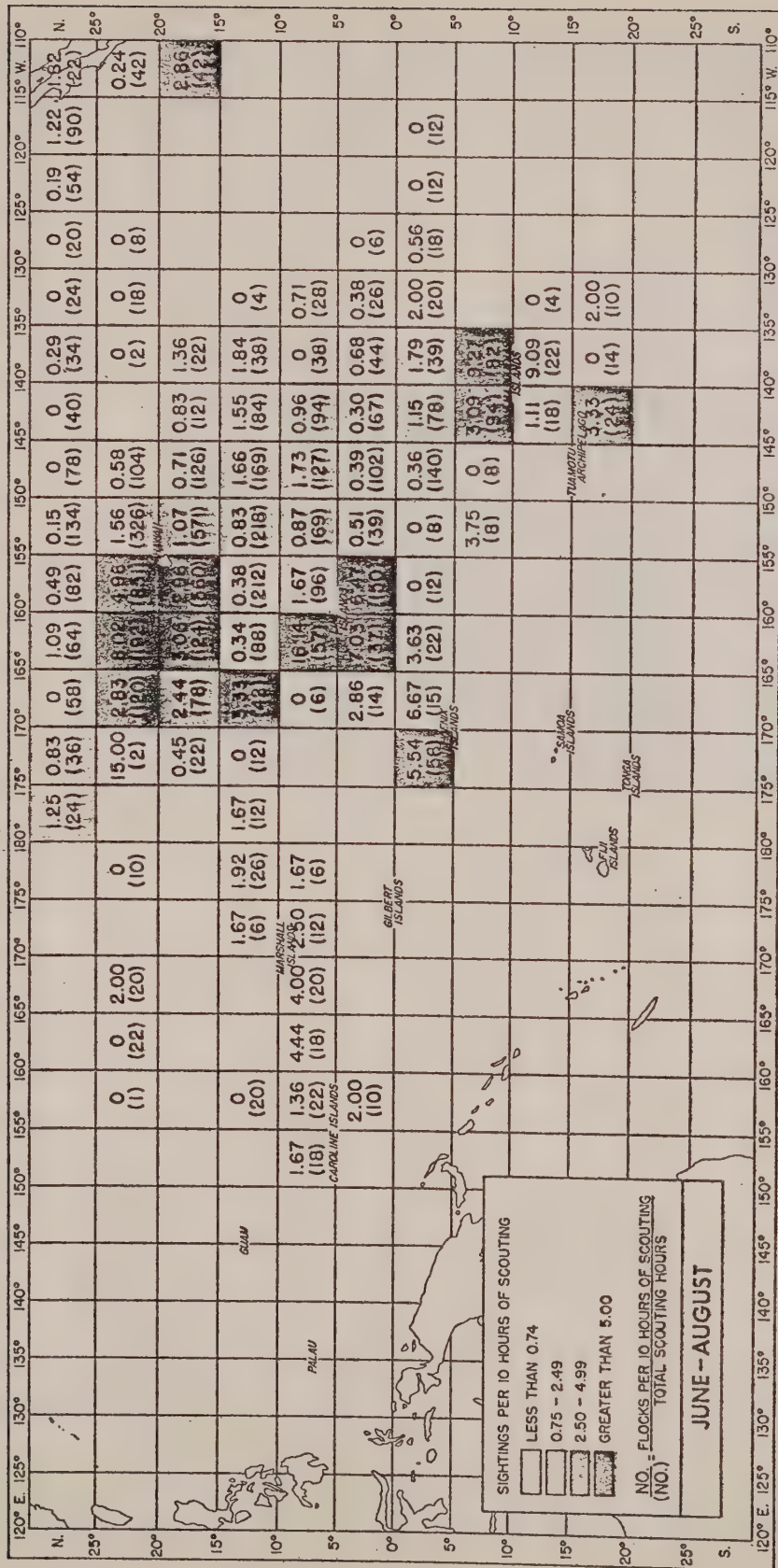


Figure 360.--Bird flock sightings by National Marine Fisheries Service

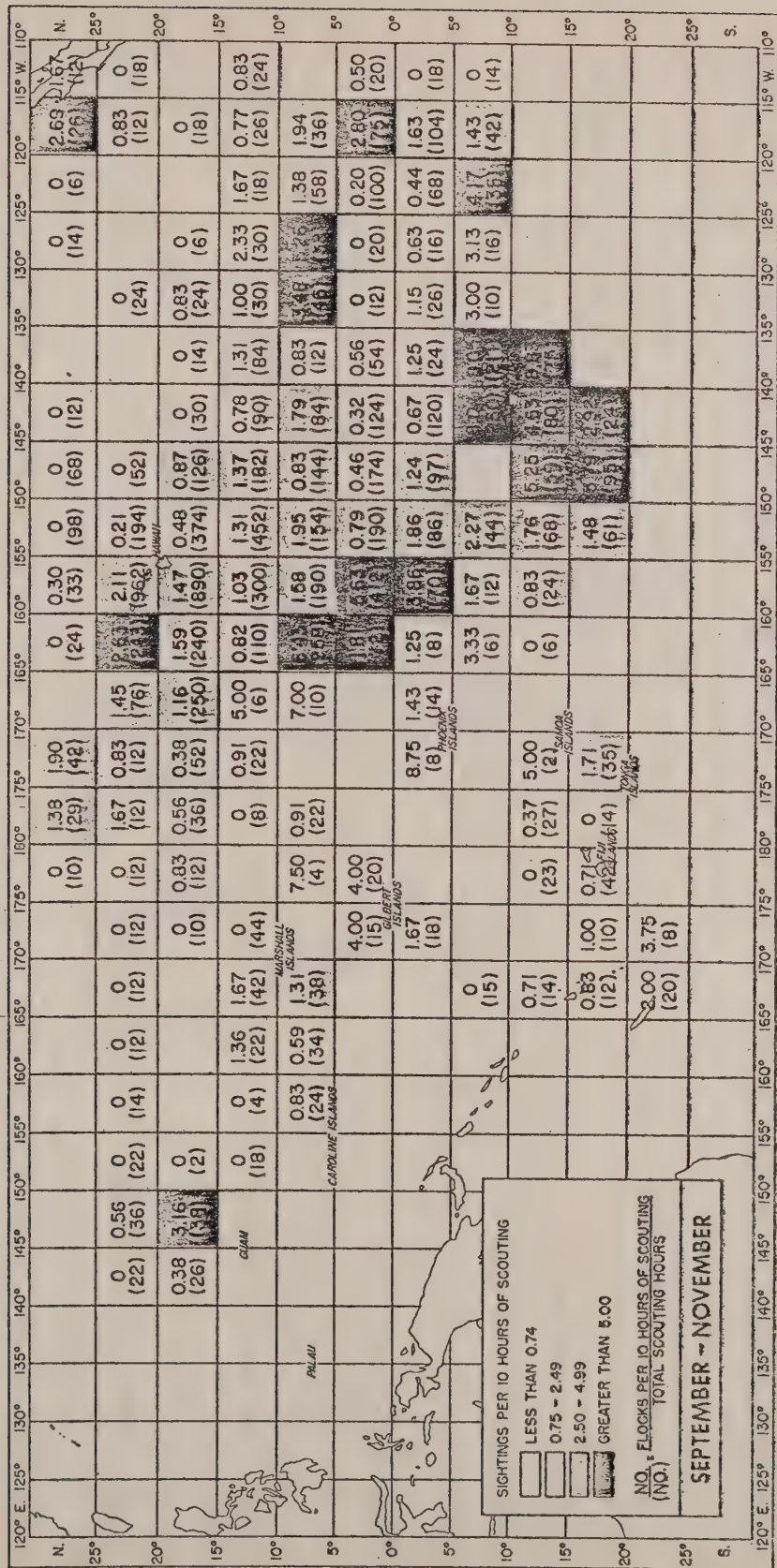


Figure 36d.--Bird flock sightings by National Marine Fisheries Service vessels, September-November 1950-72 (Naughton 5/).

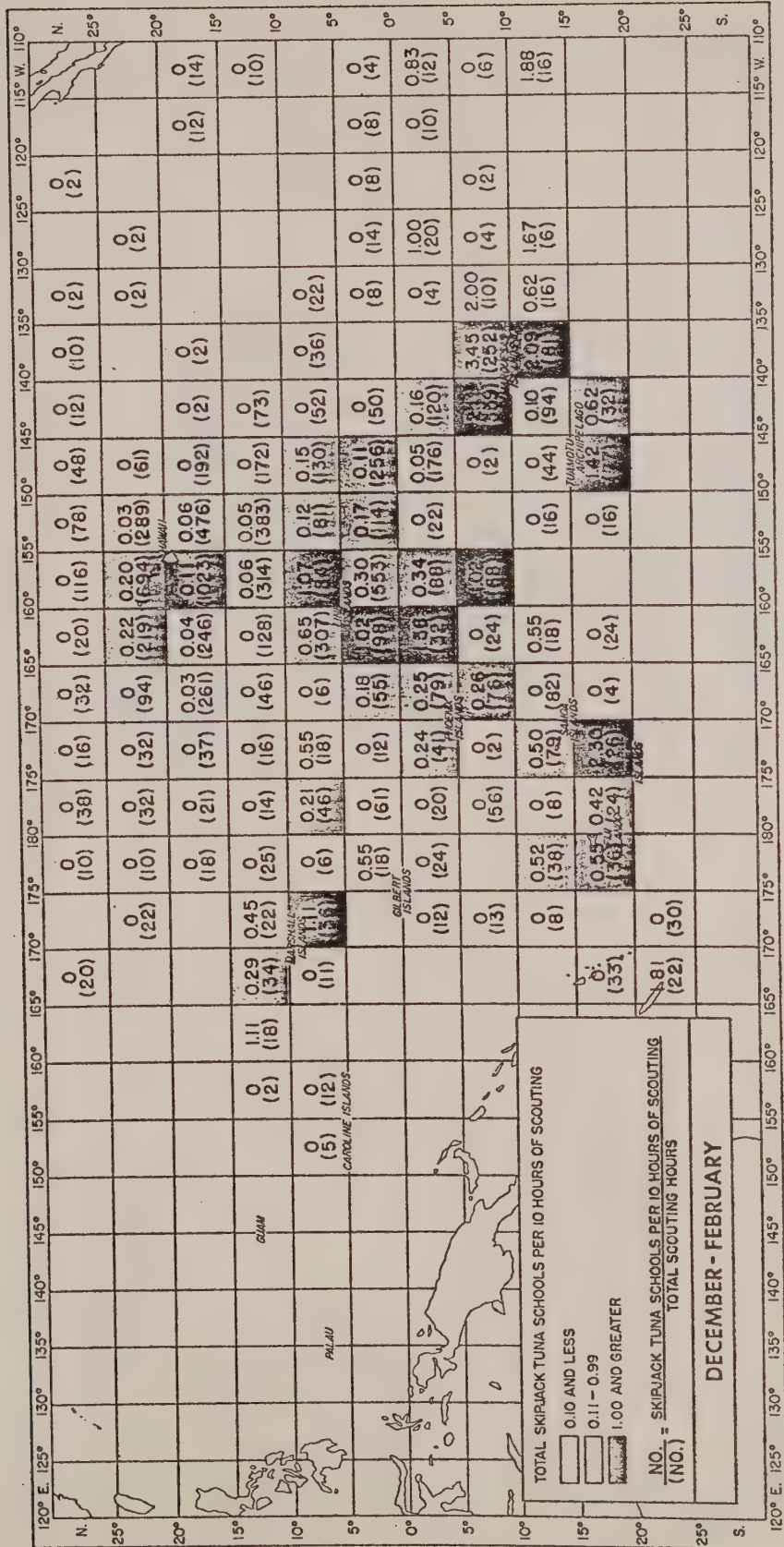


Figure 360.--Skipjack tuna school sightings by National Marine Fisheries

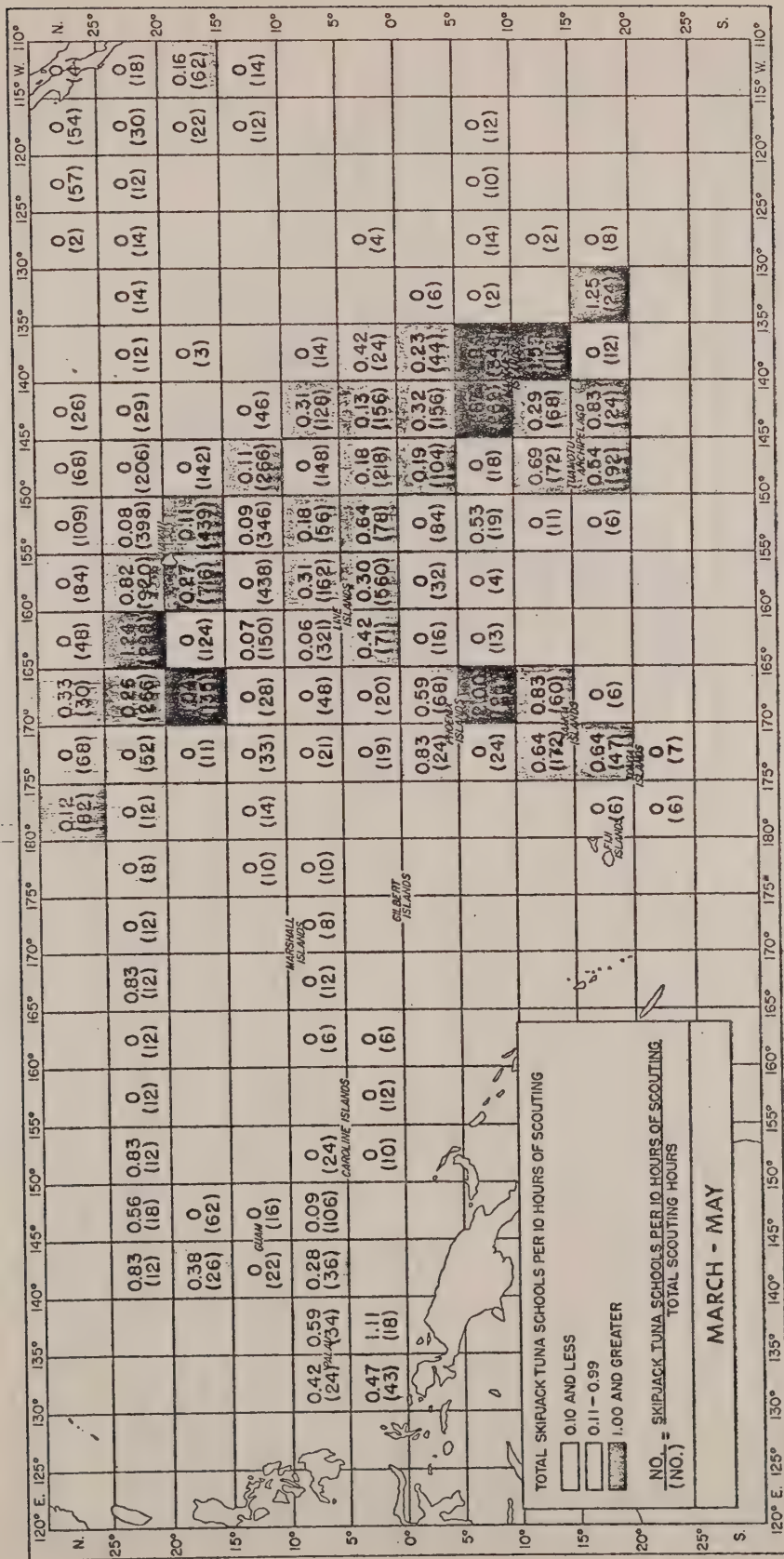


Figure 36f. Skipjack tuna school sightings by National Marine Fisheries

Service vessels, March-May 1950-72 (Naughton 3/).

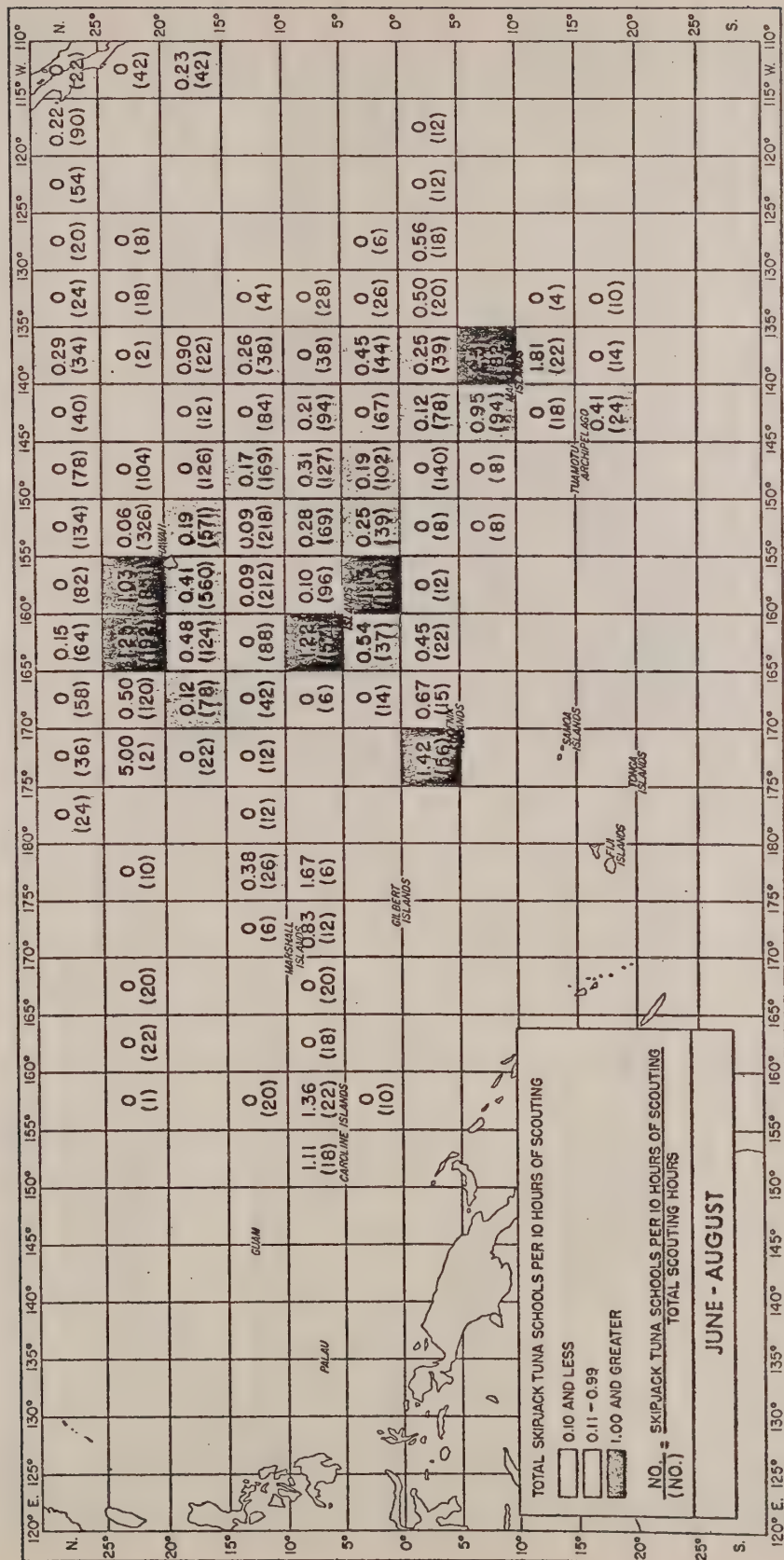


Figure 36g. Skipjack tuna school sightings by National Marine Fisheries

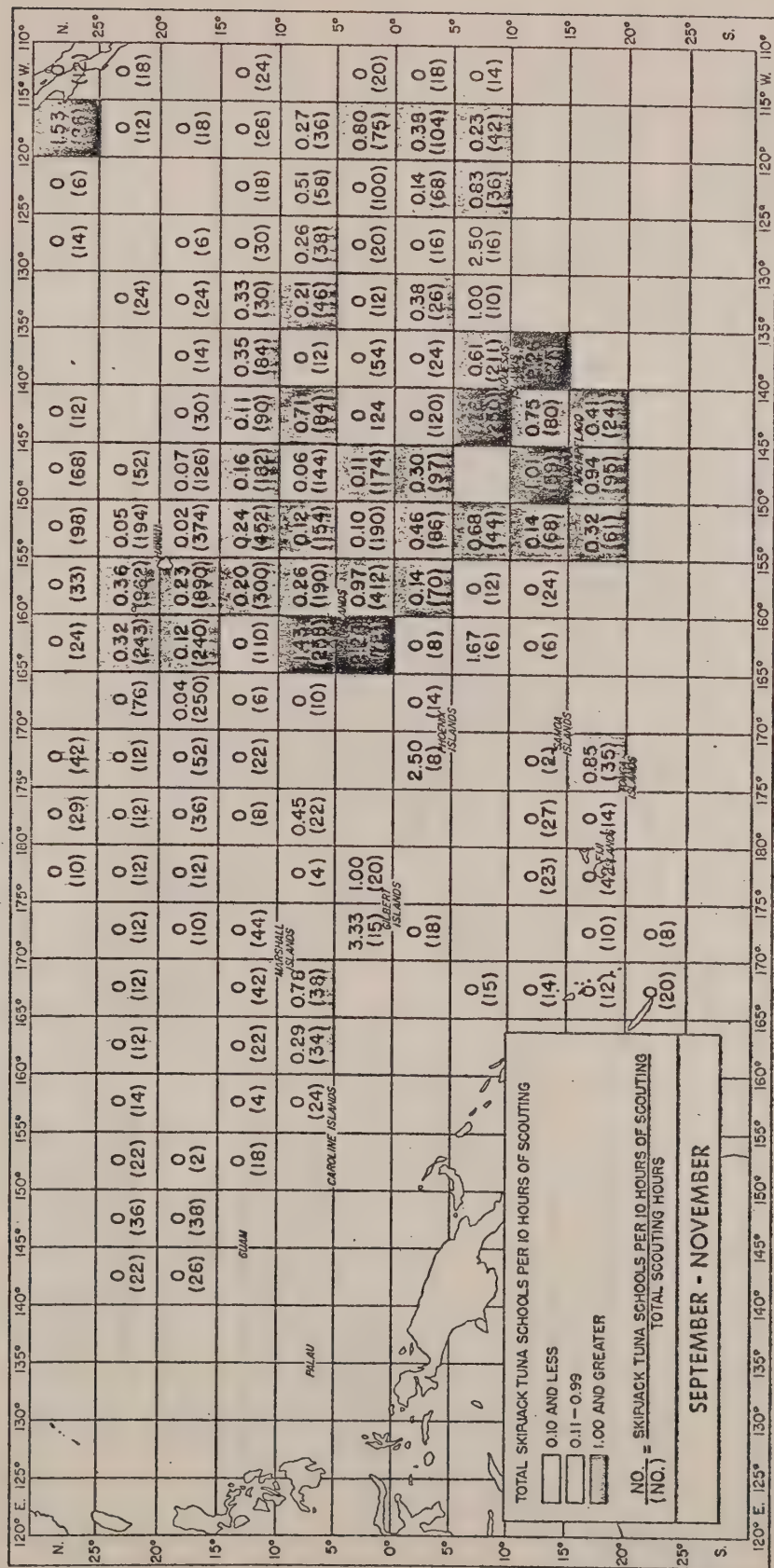


Figure 36h. Skipjack tuna school sightings by National Marine Fisheries

Service vessels, September-November 1950-72 (Naughton 3/).

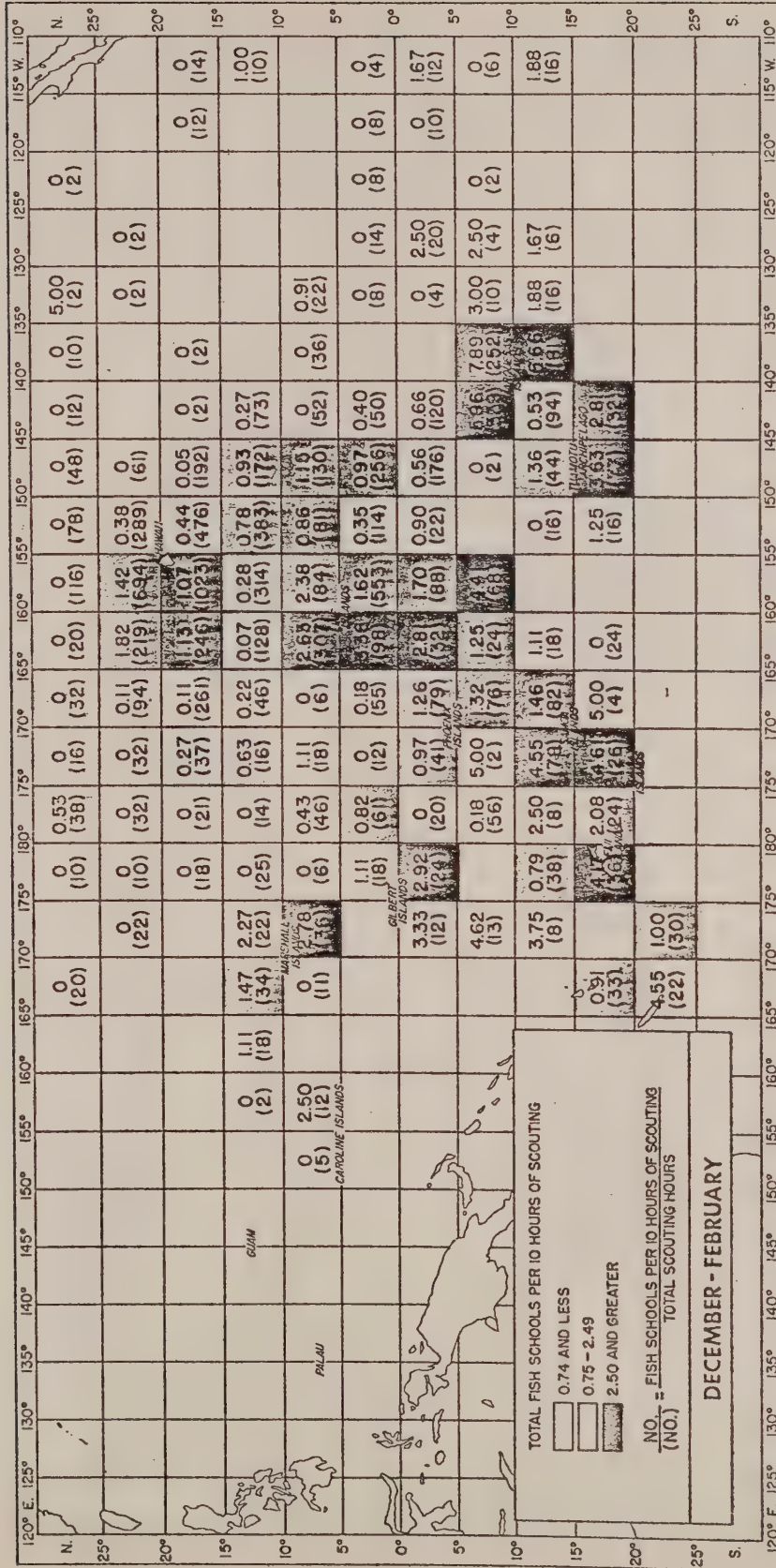


Figure 361. Total school sightings by National Marine Fisheries

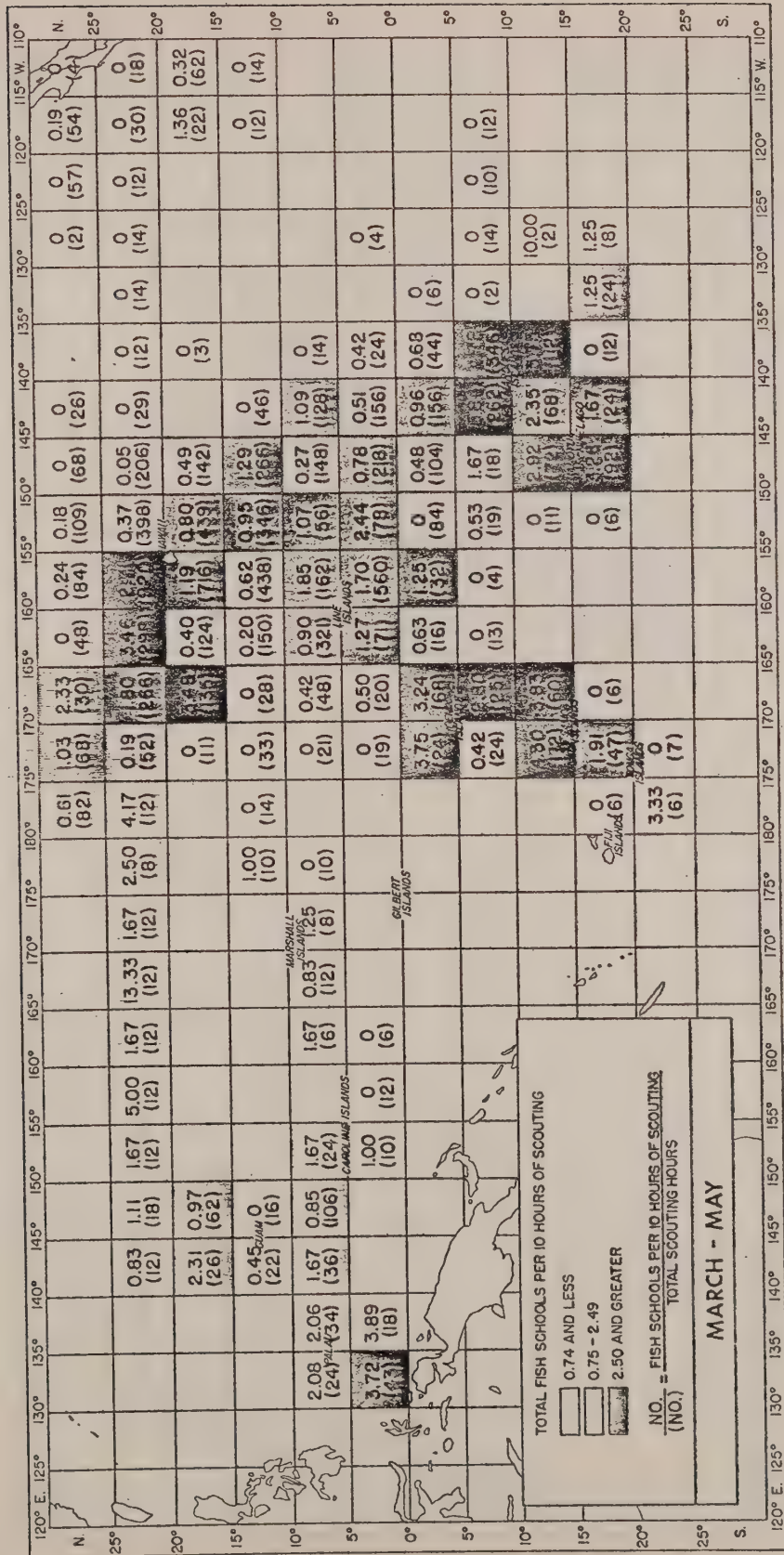


Figure 36j. Total school sightings by National Marine Fisheries Service vessels, March-May 1950-72 (Naughton 5/).

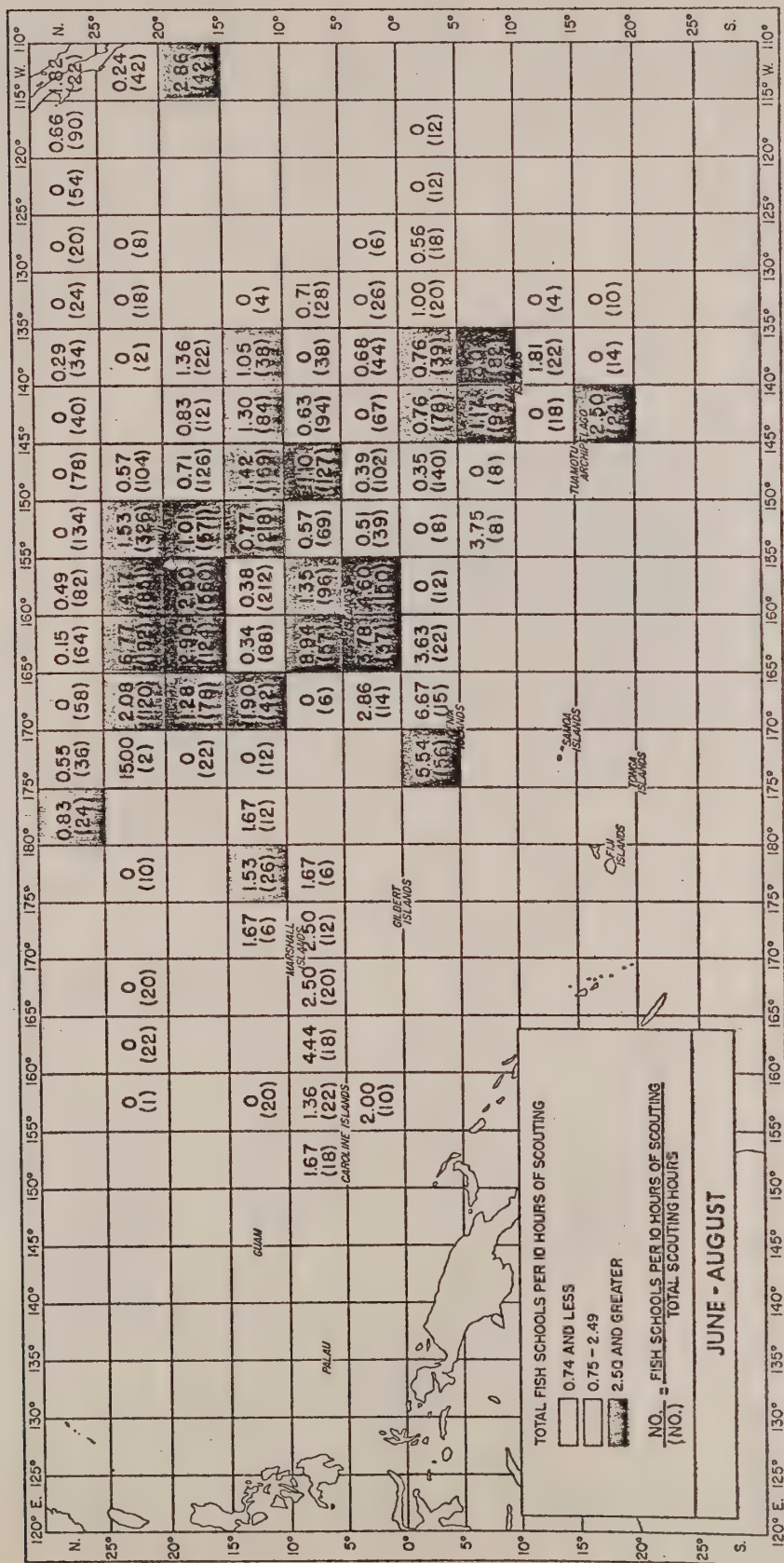


Figure 361--Total school sightings by National Marine Fisheries

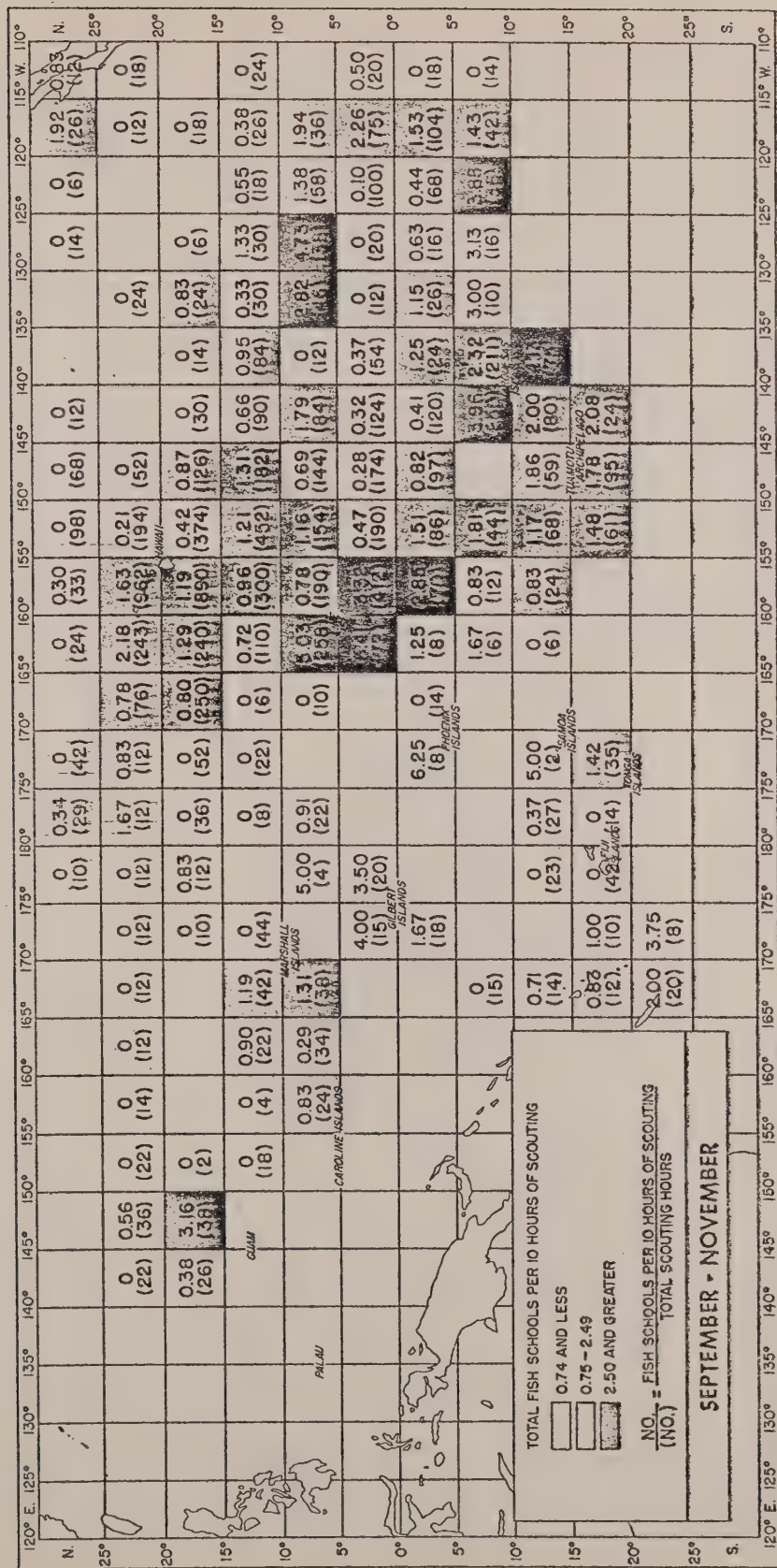
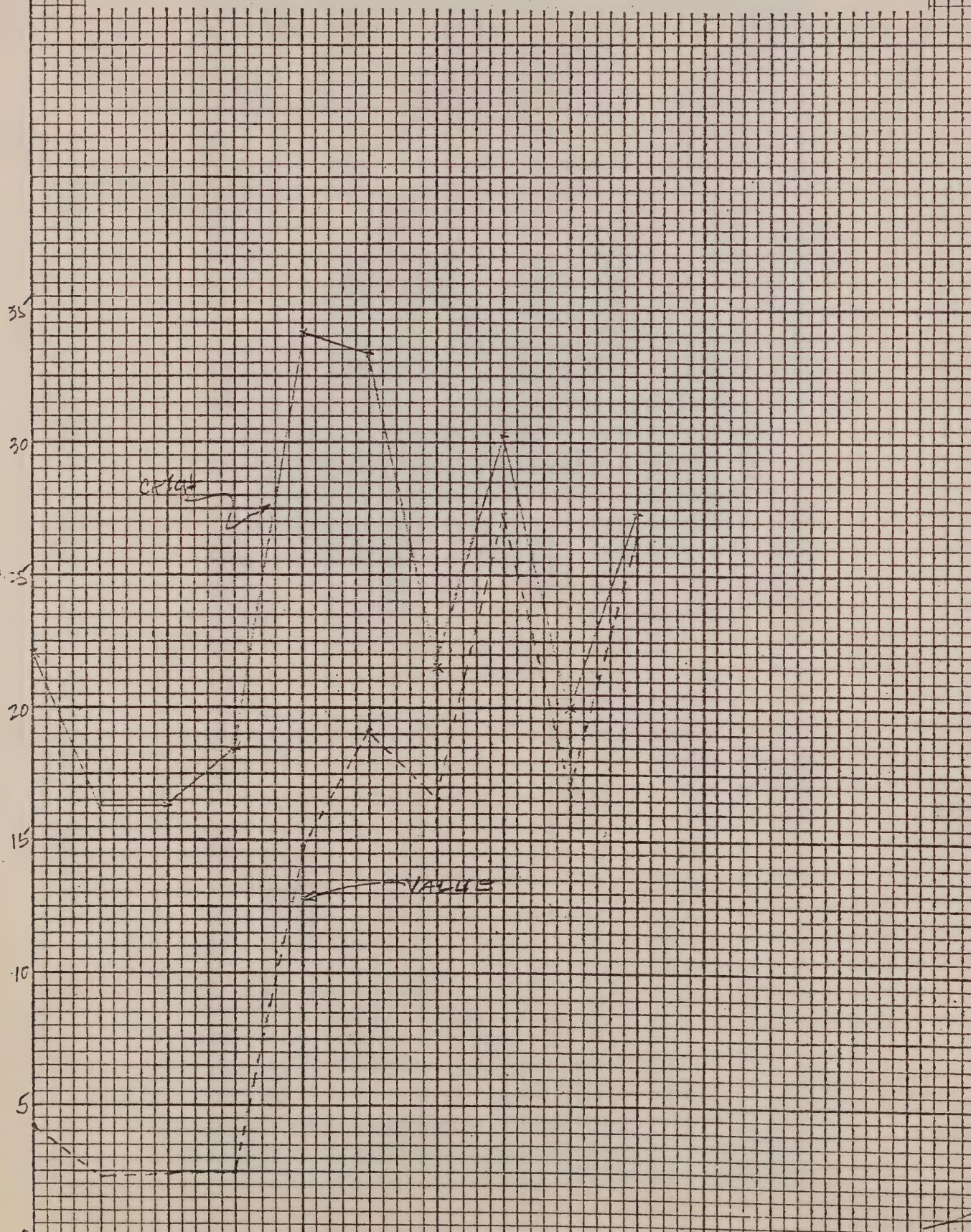


Figure 36L.--Total school sightings by National Marine Fisheries

Service vessels, September-November 1950-72 (Naughton 3/).

Figure 37.--Annual catch and value of all species caught by handline
fishing at Necker Island, 1966-75.



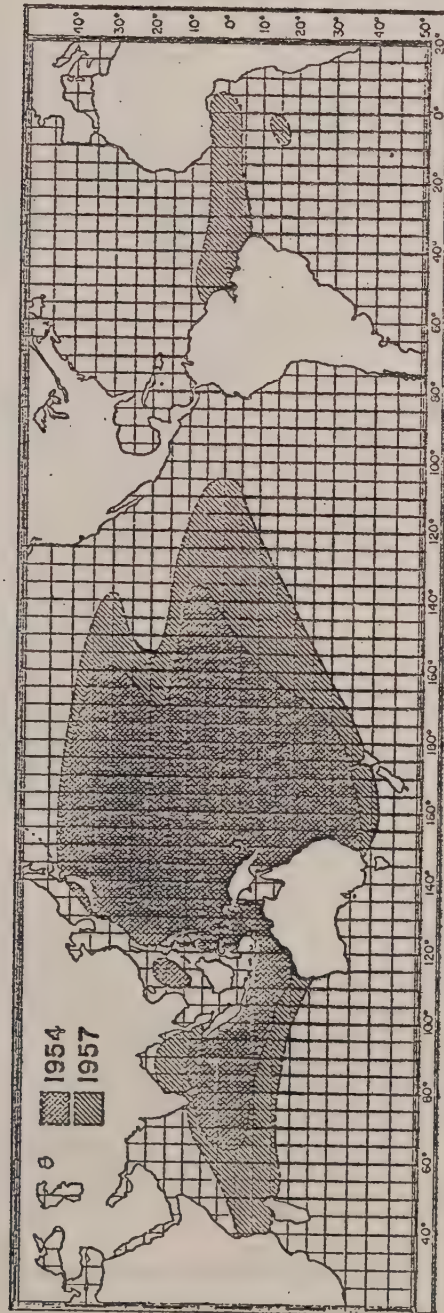


Figure 38.--Distribution of Japanese high-seas tuna fishing grounds,
1954 and 1957 (Shomura and Uchida ⁴/₅).



Figure 39.---Distribution of Japanese high-seas tuna fishing grounds,

1962 (Shomura and Uchida ⁴/₁).

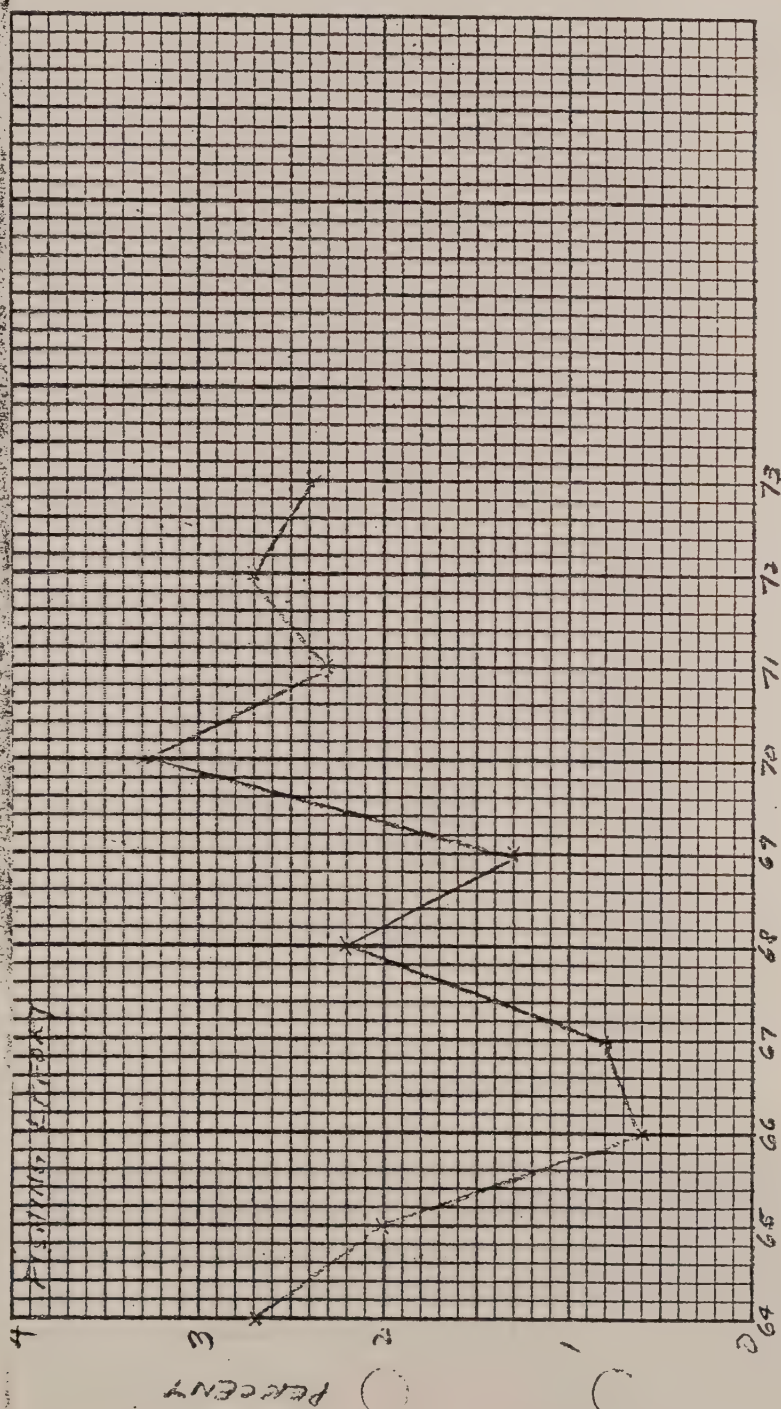


Figure 40.---Percentage of the North Pacific longline fishing effort
of Japanese vessels expended in the NWHI region in 1964-73.

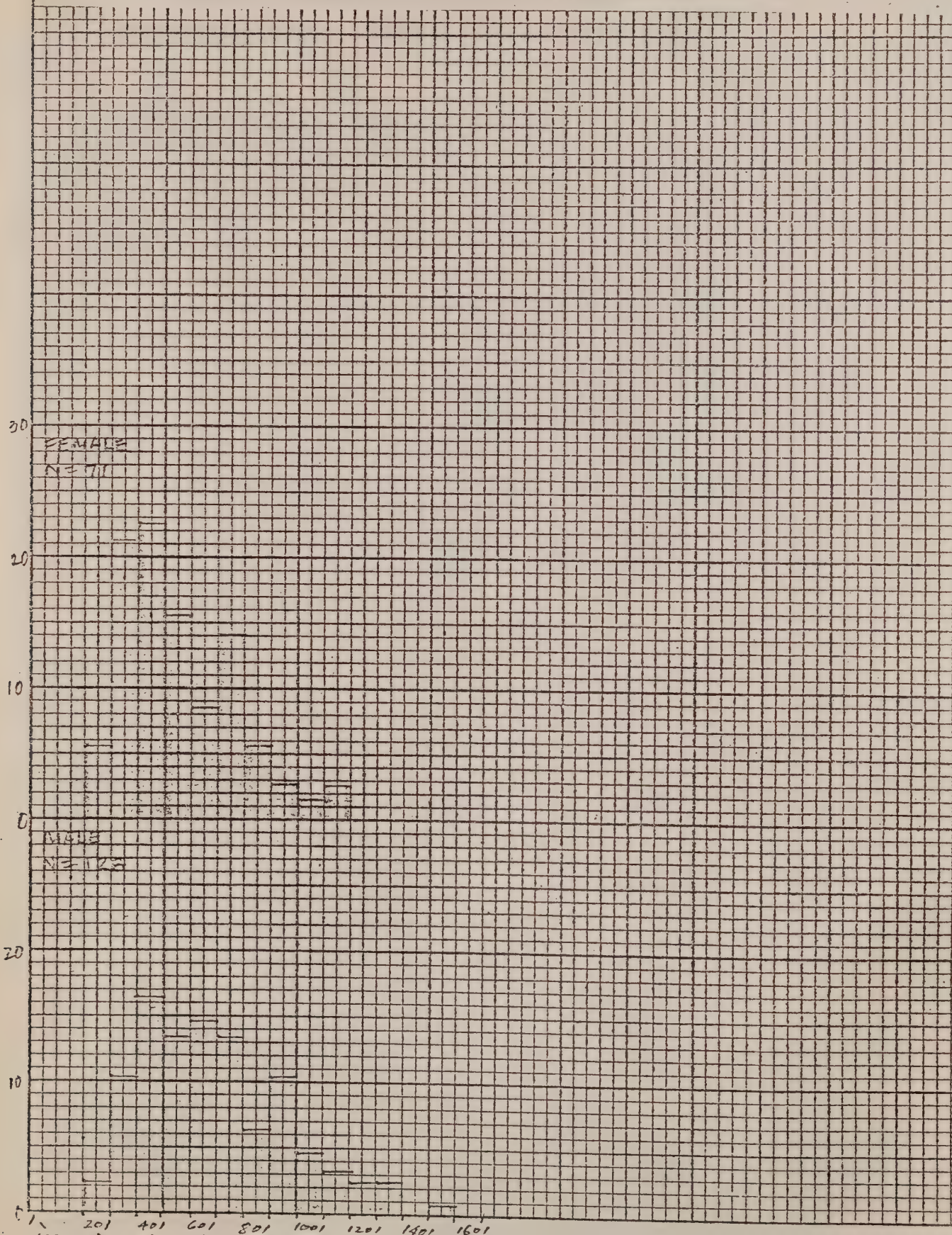
Figure 42.--Percentage length frequency distribution of skipjack tuna and kawakawa caught during exploratory pole-and-line fishing in NMHI waters.

REYNOLDS
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0
30
40
50
60
70
80

Figure 43.—Percentage weight frequency distribution of spiny lobsters caught during exploratory trap fishing in NWHI waters.



MULTIOBJECTIVE DECISIONS AND THE
FISHERY CONSERVATION AND MANAGEMENT ACT OF 1976

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The Fishery Conservation and Management Act (FCMA) of 1976 was passed by Congress both to prevent the decline of present fisheries and to encourage the development of under- or nonutilized fisheries. The intent of the FCMA is clear: Fisheries provide a multitude of benefits, such as economic, recreational, food production, etc., all of which are worthy objectives of management. At the same time the FCMA emphasizes the need to manage the fisheries in a manner that insures the continuation of the stocks and the benefits derived from the stocks. In order to carry out this law, eight regional management councils have been created, which have the responsibility to create management plans for each of the stocks under their jurisdiction.

In practice, the FCMA is being interpreted as requiring the regional councils to calculate a single number for each stock, the "optimum yield" (OY) for the stock. The criteria to calculate the "optimum yield" and to develop management measures are varied indeed in the FCMA. For example, OY is defined as:

"...means the amount of fish--

- (A) which provides the greatest overall benefit to the Nation, with particular reference to food production and recreational opportunities; and
- (B) which is prescribed as such on the basis of the maximum sustained yield from such a fishery, as modified by any relevant economic, social, or ecological factors."

and management measures are required to:

- "(5) Conservation and management measures shall, where practicable, promote efficiency in the utilization of fishery resources; except that no measure shall have economic allocation as its sole purpose.
- (6) Conservation and management practices shall take into account and allow for variations among, and contingencies in, fisheries, fishery resources, and catches.
- (7) Conservation and management measures shall, where practicable, minimize costs and avoid unnecessary duplication."

and OY again is defined as:

"The term 'optimum' is defined in this context...to mean the amount of fish from a fishery which if produced, will provide the greatest overall benefit to the Nation (especially in terms of food production and recreational opportunities) and which is prescribed for that fishery on the basis of the maximum yield sustainable therefrom (a biological measure) as modified by any relevant economic, social or ecological factor."

Some concern has arisen about how the regional concerns are to incorporate these myriad objectives into a management plan (see remarks prepared by Dr. James Crutchfield to Pacific Region Management Council^[2]). Certainly the plans should not be whatever the councils want, but should be required to adhere to some kind of objective guidelines or methods in preparing and justifying the management plans.

Dr. Crutchfield proposes returning to "maximum sustained yield" (MSY) as "the reference point for council deliberations on OY. We would depart from it in a measured, justified, and explained way..." to include other criteria or objectives into the management plan. What concerns Dr. Crutchfield is that the FCMA requires the councils to develop management plans based on multiple, probably conflicting objectives, and there appears to be no "objective" method of determining plans in such situations. The purpose of this paper is twofold. First, a consistent terminology and methodology is presented, which allows us to define what we mean by a policy, a "good" policy, and an "optimal" policy. This terminology and methodology can be used in either the single or multiple goal setting. Furthermore, a policy as we define it, takes into account variations in stock size, catch, environmental factors, etc.

Second, using the framework provided in the previous section, we see to what extent we can define sustained yield for a multiobjective problem, and consider what approach Dr. Crutchfield has suggested in his comments. We show that there are several other approaches available which appear to us to be more suited to the responsibilities of the regional councils. This paper is the descriptive framework of a paper to be presented at the Joint ORSA-TIMS National meeting (San Francisco, May 1977) where some of the mathematical and algorithmic aspects of "good" policies for managing fisheries will be discussed.

I. States, Actions, and Policies

In order to be able to clearly talk about sustained yield and multiobjective decisionmaking, we must develop precise definitions of what we mean by policies, decisions and "optimal" policies. Our definitions are borrowed from the dynamic programming literature (see Denardo^[5]). Other definitions are possible, but these particular definitions have a consistency that can be used in mathematical formulations of the problems.

The first part of a decision problem is to decide the length of the planning horizon T , that is, the number of periods into the future that will be included in our assessment of how well we are doing. Next, we must have a set of states that describe the system at some point in time. In a fisheries context, the state might be the stock size at the beginning of the period, or the size of each age class, etc. Associated with each state are a set of possible actions or decisions. The decision might be the amount of fishing effort this period, or the age-specific harvest rate, etc.

In each period, given the state and the decision, we must have a transition function which tells us the state at the start of the next period. The transition function need not be deterministic: that is it may only describe with what probability we expect to reach a given state in the next period, knowing our state and decision this period.

We can now define what we mean by a policy (we restrict ourselves to "feasible" policies, that is ones that are attainable given the dynamics and constraints of the system). A policy is a contingency plan that describes, for each possible state in each and every period in the planning horizon, what action to take in that period. The reason for such a general definition is that our transition function may not be deterministic. We do not know what state we will be in in any period in the future, so we must develop a plan which considers all possible states.

Let us assume that we have some means of comparing the time streams of period by period returns from every policy. For example, we might assume that in each period t there is a return function $G_t(x, y)$ which describes the return for each state x and decision y . In this case, we might want to:

$$\text{maximize } E \sum_{t=1}^r G_t(x_t, y_t)$$

where E is the expectation (average) operator. Or else we may have developed a utility function to compare the time streams, as in Keeney^[6]. In either case, by an optimal policy we mean a policy that produces the greatest return given the desired method of comparison.

A complete discussion of optimal policies for renewable resources can be found in [1, 8, 9, 10, 13]. As an example, assume that x_t is the stock size at the beginning of period t , y_t is the stock size at the end of period t , that there is a return from

harvest in period t of $\alpha^{t-1} p_t (x_t - y_t)$, $0 < \alpha \leq 1$ (that is linear benefits from catch, discounted by a rate α) and that the population dynamics are given by $x_{t+1} = s[y_t, D_t]$ where D_t is a random variable reflecting the influence of the environment, inaccurate measuring or imprecise modeling. Then in each period t , an optimal policy is described by a base stock size x_t^0 (see Table 1).

Table 1.--Optimal policy for linear returns.

Population size at beginning of period	Optimal catch size during period	Optimal population size at end of period
$x_t > x_t^0$	$x_t - x_t^0$	x_t^0
$x_t \leq x_t^0$	0	x_t

If the initial population size is greater than the base stock size, then it is optimal to harvest to the base stock size x_t^0 . Otherwise, it is optimal not to harvest. Notice that the policy does not call either for sustained catch or for sustained effort. An optimal policy is state specific, and the amount the optimal catch will vary will depend on the amount of fluctuation in the "production" (transition) function.

The main point of this example is to clarify what we mean by "optimal," "policy," and decisions, and to show why uncertainty makes it necessary to use such definitions.

II. Multiobjective Decisions

Multiobjective decisionmaking has been an active area of recent study in the field of operations research (see the extensive bibliography published in Zeleny^{[17]*}). The main interest of study is decisionmaking when the multiple goals are conflicting in their aims. In what sense is it possible to talk about "optimal" or "good" policies. For clarity of exposition, we consider at first only the static problem, that is our planning horizon consists of a single period. Assume for each state x (possibly a vector) there are j possible decisions or actions, given by the vector $y = (y_1, \dots, y_j)$. In a fisheries context, the j actions might be the amount of fishing effort allowed different sectors of the fishery. Given the state x , and the decision y , we assume there are k return functions $j \leq k$, $G^1(x, y), G^2(x, y), \dots, G^k(x, y)$ each of which independently measures the benefit in some sense, from observing state x and making the decision y . For example, G^1 might represent the economic benefit, G^2 might represent food or protein production, G^3 might represent benefits to recreational fishermen. Then, by an "optimal" policy for state x , $y^*(x)$, we mean a realizable decision $y^*(x)$, such that:

$$G^i(x, y^*(x)) \geq G^i(x, y)$$

for $i = 1, \dots, k$

and for all attainable y .

* In this section, references to authors mean the cited works in this bibliography, unless a specific alternate reference is given.

That is, the decision $y^*(x)$, out of all possible decisions, is simultaneously optimal in each and every objective. For conflicting objectives, rarely does such a policy exist, and real world experience confirms this observation. For example, in the California anchovy fishery, policies that are economically optimal for the reduction fishery overfish in terms of maintaining anchovy stocks as food for recreational fish.

While we may not be able to talk about "optimal" policies in the multiobjective case, we can define "good" policies. However, it is worth noting that a "good" policy will depend on both the objectives involved and on the particular definition of "good."

Multiobjective decisionmaking has taken two basic approaches: Prior weighting of the objectives and posterior weighting of the objectives. In the first category are methods such as determining utility functions, goal programming, and just plain assigning weights. In the latter category are programming techniques to determine "nondominated," "noninferior," "efficient," or "weakly-maximal" decisions.

Several examples of using utility functions in managing fisheries have appeared recently (see Tomlinson, Verlinsky, or Keeney^[6]). A utility function reduces the multiobjective problem to a single dimension. That is, each possible combination of the k objective functions is reduced to a single number that represents our overall preference for that particular mix of returns. In practice, carefully chosen pairwise comparisons of returns are showed to the "decisionmaker,"

who chooses one as "preferred." Repeating this process can eventually lead to the determination of a utility function. (For a complete discussion of utility theory, see von Neumann and Morgenstein^[16]; Luce and Raiffa^[7]; Fishburn or Keeney among others.)

One type of utility function is a weighting of the k -objectives. That is, for each state x and decision y , the total return is $J = \sum_{i=1}^k \lambda^i G^i(x, y)$ such that $\sum_{i=1}^k \lambda^i = 1$. The weights are determined beforehand, and we are left with a straight optimization problem. One widely known version of this is "goal programming" (see Charnes and Cooper, or Lee). In "goal programming," rather than an objective function, there are k fixed goals, which are ranked in order of importance. The k goals are then assigned incommensurable weights, that is a higher goal is so weighted that if feasible, it will always be approached before a lower ranked goal. The problem then is to minimize the total weighted absolute deviation from the goals, which can be solved by linear programming codes. What makes goal programming nontrivial is that constraints on the problem often bring lower ranked goals into the final solution ahead of a higher ranked goal.

A priori weightings have the strong advantage that computational methods to calculate optimal policies for these problems are available. However, it is our feeling that for most problems arising from the FCMA that this is not the approach to take. First, it is not at all clear whose utility function should be determined in

managing a fishery. The regional management council? The executive director of the council? In a sense, this line of reasoning puts the council ahead of the law. Dr. Crutchfield's remarks cited in the introduction are relevant here--the councils are not set up to do whatever they want. Moreover, we have little experience at multi-objective management for fisheries, and it is our feeling that few people will have a good intuitive feel for what a stated preference means in terms of its effects on each segment of the fishery. However, there are certain cases where these techniques seem most applicable. The tuna-porpoise problem seems to us to be a good example. Unless the Marine Mammal Protection Act is severely modified, the law has made the decision that goals concerning maintaining porpoise are more important than economic goals of the tuna industry. In fact, as now interpreted by the courts, the goal of maintaining the porpoise is incommensurably more important. Thus, we have a goal programming like problem. If Senator Hayakawa's bill passes the senate, the weighting will be reversed, and again we are reduced to an optimization problem that is relatively simple. Of course we have our own preferences on this particular problem, but our point here is to demonstrate the applicability and limitation of our procedures.

The "posterior" methods do not produce a single solution. Rather they are procedures that eliminate policies so that what is left are a set of policies none of which can be said to be "better" than any of the other policies in the set. For example, Yu has developed the concept of a "nondominated" solution (see Yu; Yu and

Zeleny; Leitmann and Yu; Bergstresser, Charnes, and Yu). Let $G(x, y)$ represent the vector of k objective function $G^1(x, y), \dots, G^k(x, y)$. Let $G(x, y^*)$ and $G(x, y)$ be two alternate values of the vector. Associated with each vector of returns G is a "domination structure" $D(G)$, that is $G(x, y) \neq G(x, y^*)$ and $G(x, y)$ is contained in the set defined by $G(x, y^*) + D(G(x, y^*))$ then $G(x, y)$ is said to be dominated by $G(x, y^*)$. A particular example of a domination structure is given by:

$$D(G) = \{(d_1, d_2, \dots, d_k) \mid d_1, d_2, \dots, d_k \leq 0\}$$

with strict inequality holding for one component. This domination set states that an increase in the value of any objective function is always preferred. This is also the domination structure which defines a "Pareto optimal" or "efficient" point. That is $G(x, y^*)$ is "Pareto optimal" if there exists no attainable y such that

$$G^i(x, y) \geq G^i(x, y^*) \quad i = 1, \dots, k$$

with one of the k inequalities being a strict inequality. For example, consider these four vectors of "returns":

$$(2, 4, 7, 1); (8, 5, 9, 1); (3, 5, 2, 2); (4, 7, 7, 6)$$

The second and fourth vectors are Pareto optimal. To see this, note:

$$(8, 5, 9, 1) \geq (3, 5, 2, 2)$$

$$(8, 5, 9, 1) \geq (2, 4, 7, 1)$$

$$(4, 7, 7, 6) \geq (3, 5, 2, 2)$$

$$(4, 7, 7, 6) \geq (2, 4, 7, 1)$$

However, there is no simple ordering between (8, 5, 9, 1) and (4, 7, 7, 6). Thus each is in some sense a "good" policy (or returns from a "good" policy).

Several authors have shown that in many instances, particularly if the objective functions are linear or concave and nondecreasing, then each efficient point is equivalent to the optimal point for some linear combination of the k -objectives, that is for some λ^i , $i = 1, \dots, k$, $\sum_{i=1}^k \lambda^i = 1$ and with $J = \sum_{i=1}^k \lambda^i G^i(x, y)$. Each efficient point represents some weighting of the k objectives, though not all weightings are equivalent to an efficient point. This is why we have termed these procedures "posterior" procedures, in that the weighting(s) are found rather than determined beforehand. These procedures have the advantage of presenting the council with a variety of alternatives, each of which represents a weighting of the objectives, and each of which is a "good" policy in some well defined sense of the word. These procedures have the disadvantage that computationally they are more difficult, and also because it is possible to have a problem that has a multitude of such "good" policies, so that little has been gained by the effort.

A final solution concept to the multiobjective decision problem is to allocate to each element y^j of the decision vector y that which it would obtain at a "competitive equilibrium." By a competitive equilibrium, we mean a point where each "player" simultaneously maximizes its return against a fixed policy of all the other "players." Thus at a competitive equilibrium, each player is

maximizing its return against the other players best strategy. If any player deviates from that point, they will decrease their own return (see Nash^[11]; DeBreu^[3]; Luce and Raiffa^[7]; or Owen^[12] for a discussion of game theoretic solution concepts). As a solution concept, competitive equilibriums or other game theoretic "solutions" leave the government, or government agency, such as the regional councils, the role of arbiter or mediator, which is a more passive role that it would seem is the intent of the FCMM. However, there is a large and growing literature on applications of game theory that lend this some appeal.

One of the main advantages of the techniques or concepts we have discussed is that they all, except perhaps for goal programming, readily extend to include multiperiod, dynamic decision problems. Now, instead of comparing objective functions from one period, there is a period by period time stream of vectors of objective functions or returns. Utility functions usually are discussed in the dynamic context, and the references cited earlier provide a good base. Leitmann and Yu extend the concept of nondominated solutions to dynamic, continuous time, deterministic models. Sobel^[15] discusses Pareto optimal and competitive equilibrium solutions to discrete time, stochastic problems, with either ordinal or cardinal preferences (see also Denardo^[4] and Sobel^[14]). Computational experience with such problems is very limited, but at least it provides a consistent framework to begin to set guidelines and to evaluate our decisions when there are multiple, conflicting objectives.

III. Maximum Sustained Yield (MSY) and the FCMA

In this section we return and evaluate Dr. Crutchfield's proposal cited in the introduction, but using the techniques and concepts we have developed. Though we do have some reservations about Dr. Crutchfield's comments, our main purpose is to demonstrate that even when we are not calculating "solutions" to specific problems, our techniques are still a useful and potent tool.

One criterion we require from all suggestions for guidelines to the councils is that all the terms be precisely defined. By precisely, we mean it is clear how to obtain a number (or numbers) from the terms, since the FCMA requires that we manage effort and catch and stock sizes. Examples of imprecise terms are statements such as "it is desired to insure the future stock sizes" or that the yield "on the average" be maintained. The problem with the first term is that if we believe stocks fluctuate in ways we cannot control completely, when we say "insure the future stock sizes" do we mean no lower than a certain size?, or within a range of sizes? Do we mean, with probability one, the stock, in all future periods, does not leave this range, or do we mean that we minimize the probability of future stock sizes departing from this range? As an example, there is some feeling that the California anchovy and sardine have natural cycles that are independent of harvesting effort. If this is assumed to be true, what does it mean to insure the future stock sizes of the anchovy--there is no policy that insure this.

The second term is vague because there are too many ways of taking a long-term average, particularly if we are averaging over a stochastically fluctuating phenomena. We will see this more clearly in a moment.

Dr. Crutchfield has advocated a guideline of returning to MSY and deviating from it in a measured, justified way. In our terminology, Dr. Crutchfield recommends a prior weighting of the goals, with MSY being given the highest weight, almost an incommensurably high weight. Thus, rather than establishing guidelines for the councils to consider in determining policy, Dr. Crutchfield has suggested the form the councils objective function should take. Presumably the rationale is that MSY is in some sense equivalent to "maintaining the stock," and it is this underlying goal that is being given the highest weight by Dr. Crutchfield. However, it is not clear that MSY is equivalent in any sense to "maintaining the stock," nor is it clear that an optimization problem which desires to minimize the probability that the stock size drops below a certain prescribed level will produce a sustained yield policy as its solution (in fact, results in [8]) suggest the opposite).

To see this more clearly, let us examine what we mean by MSY. MSY is usually defined in the context of single species, pooled age class, deterministic models. The sustained yield at any population size is the net growth in the population. The MSY is the maximum growth possible. Suppose however, growth fluctuates, so that it is

possible that if we harvest the expected growth, we may in fact reduce the population below the initial population size. Repeated instances of this certainly will not maintain the stock size. Suppose instead we assume we want to maximize the expected long run (time)-averaged growth. It follows from [8] that a constant effort or sustained yield policy is again not optimal, and in fact has the same detrimental possibilities mentioned earlier.

Suppose we are trying to balance biological goals with recreational goals. In this instance, age-specific models are probably the most useful. What does MSY mean here? Does it require a constant age specific profile, a constant total number, a periodic return to a specific profile, or what? Consider especially the difficulty if we assume there is density dependent recruitment and fluctuating rates.

There are no easy solutions to the problems that the regional councils face. However, we can require that all suggestions and policies to and from the councils meet certain guidelines. The type of guidelines we suggest is that first, all terms be defined in a way that makes clear how they are to be measured. Second, when a policy is said to be "optimal," or "good," that the sense of these words be clearly defined, that the different objectives be clearly stated, that the weightings to each objective that will occur following this policy be clearly discussed, and that the reason alternatives were rejected be mentioned. We have presented in this paper numerous definitions of "good" and "optimal," which can be

calculated from data. These do not exhaust the possibilities, but certainly suggest that we can clearly define and objectively evaluate a multiobjective decision problem.

Finally, the emphasis on a single number, "optimum yield," should be dropped, replaced instead with reasons why a particular allocation of catch, effort, entry, etc., was chosen, what this means in terms of present and potential effects, and also what it implies for present and potential yield.

Acknowledgments

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CONTRIBUTION TO NMFS ANNUAL REPORT

In response to a growing interest in the resources of the relatively untouched Northwestern Hawaiian Islands (NWHI), the Honolulu Laboratory recently began planning to gather ecological information to formulate management decisions on the long-range use of aquatic resources and the protection of the aquatic and terrestrial resources of these islands. With the exception of Midway Islands, which are under the jurisdiction of the U.S. Department of Defense, the islands comprising the NWHI, including Nihoa, Necker Island, French Frigate Shoals with La Perouse Pinnacle, Gardner Pinnacles, Maro Reef, Laysan Island, Lisianski Island, Pearl and Hermes Reef, and Kure Island, are under the administration and jurisdiction of the State of Hawaii. Kure is a designated State Wildlife Refuge and is managed by the State of Hawaii. However, the balance of the NWHI was designated a national wildlife refuge in 1909, and as such are currently under the administration and jurisdiction of the U.S. Fish and Wildlife Service. Because of the overlapping interests and jurisdictions, a Tripartite Cooperative Agreement among the National Marine Fisheries Service, the U.S. Fish and Wildlife Service, and the State of Hawaii is being negotiated to provide a detailed survey and assessment of the biological resources of the NWHI. The Honolulu Laboratory will assume the lead role in the implementation of the agreement and has designated a coordinator for the study. The Honolulu Laboratory will also have the responsibility to survey and assess the insular, seamount, and pelagic and other fish resources of the area. The U.S. Fish and Wildlife Service will be responsible for the survey and assessment of the

terrestrial resources, and the Hawaii State Division of Fish and Game will have the responsibility for the fishery resources of the "nearshore zone," which includes the splash zone and the underwater area from the shoreline to about 20 m from shore.

HARVESTING POLICIES AND THE FISHERY CONSERVATION
AND MANAGEMENT ACT OF 1976

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DRAFT FOR COMMENT

April 1977

The Fishery Conservation and Management Act of 1976 (FCMA), or Public Law 94-265, was passed by Congress to prevent future over-exploitation and overcapitalization in the fishing industry, as well as to develop underutilized fisheries to help meet the expected future increase in demand for fish products. The FCMA creates eight regional fishery management councils (hereafter just called the councils) to develop management plans for the fisheries within their jurisdiction. The councils are required to determine the "optimum yield" (OY), to allocate the yield between foreign and domestic users, and to suballocate within these groups.

As described in the FCMA, OY implies management for a variety of objectives. A management plan must include biological, recreational, economic, and social goals in determining OY and how the yield is allocated. For most fisheries, the optimum levels for all the objective considered separately are in conflict, so that one task of the councils is to develop procedures to find an optimum among multiple, conflicting objectives. In practice, this may mean developing several complementary techniques. A first step might be to find the utility functions for each of the interest groups, a procedure demonstrated by Keeney (1977) for managing salmon on the Skeena River. Then, given the resulting, conflicting utility functions, a second step might be to calculate the set of "efficient" or "Pareto optimal" policies, in order to reduce the number of policies the council need consider. Finally a bargaining procedure or other interactive method might be developed for the council to decide on one final plan.

Research in several of these areas is being conducted by the Honolulu Laboratory, National Marine Fisheries Service, and by the Western Pacific Regional Fishery Management Council. In this paper I present results for the second step of the process described above. The set of efficient or Pareto optimal policies is described for a class of dynamic, stochastic harvesting models relevant to fisheries management. Further, an extension of the usual dynamic programming formulation that allows a vector-valued return function rather than the usual real value return function.

I have shown previously (Mendelssohn 1976a, 1976b, 1977; Mendelssohn and Sobel 1977) that dynamic, stochastic harvesting models are highly structured capital accumulation models that possess a highly structured optimal policy function. Similar structure in the vector maximization problem makes it possible to describe the set of efficient policies solely from knowing the single objective optimal policy functions. Also, I show that it is possible to obtain readily several points of interest within the efficient set.

Let the k -vector J^* be the optimum vector, and let the k -vector J be the expected return from a given policy. That is, J^{*i} is the expected return for objective i when it is the sole objective and an optimal policy is followed. J^i is the expected return to objective i following some (any) policy.

The "p-regret function" $R_p(J)$ is defined as:

$$R_p(J) = \left(\sum_{i=1}^k (J^{*i} - J^i)^p \right)^{1/p} \quad p < \infty$$

where it is convenient to let $R_\infty(J) \equiv \max_i (J^*_i - J^i)$. It is desired

to find the feasible return vector J that minimizes $R_p(J)$ for different values of p . I consider the case $p = 1$, or total group regret, and $p = \infty$, the Chebyshev problem. A third criterion of interest is the policy that is optimal for a convex combination of the k -objective functions using $\frac{1}{k}$ for the weights. I refer to this as the "equitable" policy. The dynamic, stochastic models considered in this paper have the interesting property that a policy which is equitable also is Chebyshev optimal and minimizes the total regret.

II. Notation and Development

Describing a vector-valued stochastic model requires a great deal of notation. The glossary at the end contains a complete list of the notation used. As much as possible the notation is consistent with Mendelssohn (1976b) or Mendelssohn and Sobel (1977), since the results presented here rely on the single-objective methods in those papers.

The fishery is being managed for a planning horizon of T periods $T < \infty$. The periods are subscripted by t $1 \leq t \leq T$. Alternately, $n = T - t + 1$, the number of periods remaining in the planning, is used as the subscript. The infinite horizon problem can be treated by allowing n to approach infinity. At the beginning of each period an initial stock size x_t is observed, with $x \in X$, the set of possible stock sizes. The stock is harvested by j user groups, and each group catches z_t^j , $i = 1, \dots, j$ during period t . Let the j -vector $z_t = (z_t^1, \dots, z_t^j)$ be the

vector of the j catches during period t . The stock size in period $t + 1$ is assumed to be a random function $s[\cdot, \cdot]$ of the stock left after harvesting has ceased, that is:

$$x_{t+1} = s \left[x_t - \sum_{i=1}^j z_t^i, D_t \right] \quad (2.1)$$

where $D_1, D_2, \dots, D_T$ are independent, identically distributed random variables distributed as the generic random variable D .

For a given stock size and harvest vector (x, z) , each of the j users has a one period return given by the real-valued function $g_t^i(x, z)$. There may be $k - j \geq 0$ other groups that have an interest in how the stock is managed. Their one period returns are denoted by $g_t^i(x, z)$, $i = j + 1, \dots, k$. Let the k -vector $G_t(x, z) = (g_t^1(x, z), \dots, g_t^k(x, z))$. The natural constraints on the problem are:

$$\begin{aligned} x_t &\geq \sum_{i=1}^j z_t^i \\ x_t, z_t^i &\geq 0 \quad i = 1, \dots, j \quad \text{for all } t \end{aligned} \quad (2.2)$$

For a k -vector valued function G with components g^i , $i = 1, \dots, k$ a policy z^* (resp. a return vector J^*) is termed "efficient" or undominated if there is no other feasible policy (resp. no other feasible return J) satisfying:

$$G(x, z) \geq G(x, z^*) \frac{1}{\quad} \quad (2.3)$$

That is, a policy is efficient if there is no other feasible policy that does at least as well in $k-1$ of the objectives and strictly better in the k^{th} objective.

For any k -vector valued function $G(x, z)$, let X be the set of all possible states, $Z(x)$ the set of feasible decisions at $x \in X$, and $C \equiv \{(x, z) : x \in X; z \in Z(x)\}$. Let Λ be the set of efficient return vectors of G for $(x, z) \in C$, and Ω the set of G such that $(x, z) \in C$. Define the operator $vmax$ as a map from $\Omega \rightarrow \Lambda$, that is it maps the set of feasible vector returns into the set of efficient vector returns. Any $G(x, z) \in \Lambda$ implies a subset of C such that (x, z) is an element of the subset if and only if $G(x, z) \in \Lambda$. At times I use the slightly abused notation of having $vmax$ map C into its efficient subset. The use, however, should be clear from the context.

For the dynamic problem, let E denote the expectation operator. Then the problem of finding the set of efficient policies can be expressed as:

$$vmax \ E \left(\sum_{t=1}^T G_t(x_t, z_t) \right) \quad (2.4)$$

subject to (2.1), (2.2)

^{1/}When comparing two k -vectors x and y , $x \geq y$ implies $x^i \geq y^i$ for all i ; $x \leq y$ implies $x \geq y$ but $x \neq y$; $x > y$ implies $x^i > y^i$ for all i .

A history H_t is a feasible sequence of states, decisions, and random variables up to time t , that is:

$$H_t = \left\{ x_1, z_1, D_1; x_2, z_2, D_2; \dots; x_{t-1}, z_{t-1}, D_{t-1}; x_t \right\}$$

By a policy, I mean a function which for each period and all possible histories describes what decision to make. Let $V_t(\delta|H_t)$ be the expected value of the k objectives when history H_t has been observed, and the possibly nonstationary policy δ is followed for the remainder of the planning horizon.

Theorem 1 is the central mathematical theorem in this paper. Results along the same lines certainly are implicit in Sobel (1975, 1977); however, I know of no other reference where the dynamic programming problem is expanded to treat the vector maximum problem exactly as it is here. The proof, and the proofs of all results in this paper, can be found in the Appendix.

Theorem 2.1 For problem (2.4)

- i) A policy is efficient from period 1 if it is efficient from period t onwards, for all $t \leq T$.
- ii) An efficient policy only depends on the past history H_t through the present state x_t ; that is, the expected value of a possibly nonstationary policy δ given H_t satisfies:

$$V_t(\delta|H_t) = V_t(\delta|x_t)$$

for all H_t , δ , and t .

□

Corollary 2.1 Let $f_n^{\text{eff}}(x)$ be defined as equal to $V_n(\delta|x)$ for some (any) efficient policy δ . Then z is an efficient decision for state x in period n if and only if it is undominated for the k -vector valued function given by:

$$G_n(x, z) + E f_{n-1}^{\text{eff}}(s[x - \sum_i z^i, d^i])$$

□

If we modify f_n^{eff} to be the set of efficient vector returns, and have $G + E f_{n-1}^{\text{eff}}$ denote the set of values given by the value of G plus the value of each element in the set $E f_{n-1}^{\text{eff}}$, then corollary 2.1 leads to the multiobjective extension of dynamic programming, which can be formulated as:

$$f_0^{\text{eff}}(\cdot) \equiv 0$$

$$f_n^{\text{eff}}(x) = \text{vmax} \left\{ G_n(x, z) + E f_{n-1}^{\text{eff}}(s[x - \sum_i z^i, d]) \right\}$$

To describe the set of dynamic efficient policies, it becomes only necessary to describe the set of efficient actions in period n , given the state x . This point to set mapping is the equivalent of the usual optimal policy function in single objective dynamic programming. Given that a decision z is efficient in period n , the set of resulting efficient policies is to choose any efficient action in the following periods.

A closely related problem is:

$$\begin{aligned} \text{maximize } EJ &= E \sum_{t=1}^T \sum_{i=1}^k \lambda^i g_t^i(s_t, z_t) \\ \text{subject to } \sum_{i=1}^k \lambda^i &= 1, \quad 0 \leq \lambda^i \leq 1; \quad (2.1), (2.2) \end{aligned} \tag{2.5}$$

From standard dynamic programming arguments, a solution to (2.5) satisfies the system of recursive equations:

$$\begin{aligned} f_0^\lambda(\cdot) &\equiv 0 \\ f_n^\lambda(x) &= \max_{0 \leq \sum z^i \leq x} \{J_n^\lambda(x, z)\} \end{aligned} \tag{2.6}$$

$$\text{where } J_n^\lambda(x, z) = \left\{ \sum_{i=1}^k \lambda^i g^i(x, z) + E f_{n-1}^\lambda \left(s[x - \sum z^i, d] \right) \right\}$$

If each of the g^i are concave, equation (2.6) and corollary 2.1 imply that there exist efficient policies which change the weighting factors λ^i between periods. At first glance policies of this form may appear to be of little interest. However, the desirability of policies that have changing implied weightings can occur for several reasons. First, given the actual realization of the random process, the actual returns may be very different from the expected returns. Certain objectives may be more sensitive to this variation, and changing to a different implied weighting may compensate for this.

Second, experience may teach us that what we thought we preferred is not what we actually preferred. That dynamic efficient policies exist that change the weightings with time allows us to change preferences as we learn about the system. Rather than being uninteresting, corollary 2.1 tells us that we can switch the implied weighting midstream and still have an efficient policy for the whole planning horizon. This flexibility seems desirable.

Finally, for a real function of one-argument, f' denotes the derivative of $(f: R \rightarrow R)$ and ∇f denotes the gradient vector. For a function of two arguments $f^{[1]}$ denotes the gradient with respect to the first vector, and $f^{[2]}$ the gradient with respect to the second vector. $\nabla^i f$, $f^{[1]i}$, $f^{[2]i}$ denote the i th component of the vector. At times, one-sided or directional derivatives are appropriate; however, I feel these are clear from the context.

III. Result

A. Single decision variable

In some fisheries, only one of the groups interested in the stock actually harvest it. For example, the northern anchovy (Engraulis mordax Girard) is exploited by a reduction fishery, which uses the anchovy mainly for meal. However, the northern anchovy is considered an important food source for several important sport fish. Recreational fishing associations have expressed a strong interest in how the fishery is managed. The government has its own goals--both to insure the health of the stock and of the industry given a population that exhibits large natural fluctuations.

I derive results for the bicriterion case, and then show that similar results are valid for $k > 2$. I assume hereafter (unless otherwise stated) that $s_t[\cdot, \cdot]$ is a stationary function, and that G_t depends on time only through a discount factor α , $0 < \alpha \leq 1$. That is

$$G_t(x, z) = \alpha^{t-1} G(x, z)$$

I assume that the one period return (or utility) for each interest group depends only on the allowable catch, and that the following assumptions on g^i are valid for each user i :

- (i) $g^i(\cdot)$ is concave and continuous on the set $C = \{(x, z) : x \in X; 0 \leq z \leq x\}$
- (ii) $g^i(\cdot)$ is nondecreasing; $g^i(\cdot) < \infty$
- (iii) $g^i(\cdot)$ is uniformly bounded from below

and I assume for the transition function $s[\cdot, \cdot]$ that:

- (iv) $s[\cdot, d]$ is concave and continuous for each fixed value d on the set

$$Y = U$$

Assumptions (i)-(iv) are discussed in greater detail in Mendelsohn (1976b) or Mendelsohn and Sobel (1977). If the demand curve is such that per unit price (benefit) is nonincreasing with total supply, then $p(z) \cdot z$, the total value of the harvest satisfies assumptions (i)-(iii). Also, if the preference structure of a decision-maker is additive and risk-adverse, or multiplicative such that the log of the utility is risk-adverse, then the utility function determined by that preference structure satisfies (i)-(iii) (see Keeney 1974 for a complete discussion of conditions that generate utilities with these forms).

Assumption (iv) is satisfied by many production models. I believe that if $s[x - z, d] = ds[x - z]$ then it is sufficient that $s[\cdot]$ be pseudoconcave, which would include a more general class of production models. However, except for the linear returns case, I have not been able to prove this.

As described, the problem does not include allocation, but rather involves groups with differing valuations of the work of an allowed catch in any period. Often problems stated in somewhat different terms from my assumptions can be put into this form. For example, the Sport Fishing Institute (SFI) has called for a based stock policy to manage the northern anchovy. They prefer that the industry catch be set at 10% of the surplus over a fixed size spawning population, or else zero. It follows from the single objective results in Mendelssohn (1976b) or Mendelssohn and Sobel (1977) that this policy is optimal for some return function satisfying assumptions (i)-(iii). Assumption (iv) can be found in MacCall (1976) or Mandell (1975). Other conservation aimed objectives can often be put into a form satisfying assumptions (i)-(iii) by carefully choosing the objective function.

Theorem 3.1 is the main result for this model. It states that knowledge of the single-objective optimal policy functions is sufficient to calculate the set of Pareto optimal policies. Let $z_n^{1*}(x)(z_n^{2*}(x))$ be the optimal policy functions when objective one (two) is the sole objective being considered.

Theorem 3.1 For problem (2.4), let $k = 2, j = 1$. For fixed x , assume $z_n^{*1}(x), z_n^{*2}(x)$ are known for the two single objective problems, with $z_n^{*1}(x) \leq z_n^{*2}(x)$. Then:

- i) A decision z is an element of a Pareto optimal policy if and only if z is contained in the set $\{z \mid z_n^{*1}(x) \leq z \leq z_n^{*2}(x)\}$
- ii) The set of Pareto optimal policies for each n and $x \in X$ is to choose a z as in (i) and any Pareto optimal policy in period $n - 1$.

□

A conclusion from theorem 3.1 is that the wider the disagreement among the users, the greater the number of Pareto optimal policies. This makes it all the more important to find a smaller number of policies that have other desirable properties. One such policy might be to choose $z = 1/2(z_n^{*1}(x) + z_n^{*2}(x))$, the halfway point between the two desired policies. Other policies, as mentioned in section I, are ones that are equitable, Chebyshev optimal and minimize the total group regret. Theorem 3.2 relates these policies.

Theorem 3.2 Under the assumption of theorem 3.1, there exists an equitable policy that also minimizes the total regret and minimizes the maximum regret.

□

Only rarely will this policy be equivalent to choosing $z = 1/2(z_n^{1*}(x) + z_n^{2*}(x))$. These two policies certainly seem to be reasonable starting points for any "bargaining" procedure to determine a final policy.

So far the results have been limited to two objectives. However, corollary 3.1(2) states that the results are equally valid for $k \geq 2$. Again, let $z_n^{i*}(x)$ be the optimal policy function when objective i is the only objective considered.

Corollary 3.1 The results of theorem 3.1, with $k \geq 2$ and $z_n^{1*}(x) = \text{minimum}_{1 \leq i \leq k} \{z_n^{i*}(x)\}$ and $z_n^{2*}(x) = \text{max}\{z_n^{i*}(x)\}$ are valid, and theorem 3.2 remains correct as stated.

□

It should be noted that in using the regret functions (or even weighting) I tacitly assumed all of the objective functions are on an equivalent scale. The results are valid if they are not, but the interpretation becomes clouded. Such metrics are always affected most by the largest return with the largest spread (greater rates of change) and without proper weighting will not have any intuitive notion of fairness.

B. Allocating catch among users

In the last section, there was only one user of the resource, and the conflict was over how large a catch should be allowed that user. A second common problem is where there are several users of the resource.

A policy must decide both total allowable catch and the allocation of that catch. The problem is a dynamic allocation model.

Consider first the two user, two objective case, that is $j = k = 2$. I assume that the one period return to each user depends only on the catch allotted to that user, and that $g^i(\cdot)$ satisfies assumption (i)-(iii) for each i , and that the transition function satisfies assumption (iv).

The set of Pareto optimal policies can be defined by knowing three relatively simple functions. First, I assume that the single objective optimal policy functions, $z_n^{1*}(x)$ and $z_n^{2*}(x)$ are known. Second, I assume that the curve (as a function of λ) where $\lambda g^{2'}(z_1) = (1 - \lambda)g^{2'}(z_2)$ is known on the (z_1, z_2) coordinates. For each λ , the solution (z_1, z_2) to the equality is the point where the weighted price (derivative) to the one user just equals the weighted price to the other user, so that a small loss to the one is just offset by the gain to the other. If the problem was not dynamic, the curve defined by $\lambda g^{1'}(z_1) = (1 - \lambda)g^{2'}(z_2)$ would clearly define all efficient solutions. It is appealing that the dynamic policy should also be related to this curve, as well as to the single objective optimal policy functions. Theorem 3.3 states that this is in fact the case.

Theorem 3.3 Assume in (2.4) that $j = k = 2$, that $g^i(z)$ depends on z only through z^i , that assumptions (i)-(iv) are valid, and that the two single objective policy functions $z_n^{1*}(x)$, $z_n^{2*}(x)$ are known. Then:

- i) For each n , and $x \in X$, there is a Pareto optimal policy for z such that z is contained in the set $\{z \mid z_n^{1*}(x) \leq z^1 \leq z_n^{2*}(x)\}$ assuming $z_n^{1*}(x) \leq z_n^{2*}(x)$.
- ii) Each of these policies is equivalent to a point on the curve (as λ varies) where $\lambda g^1(z^1) = (1 - \lambda)g^2(z^2)$ on the interval $[z_n^{1*}(x), z_n^{2*}(x)]$ or else is at an end point of the interval.
- iii) A Pareto optimal policy is to choose z as in (i) and any Pareto optimal policy for the state in period $n - 1$.

□

As in the last section, the greater the conflict between the two single objective policies, the larger the set of Pareto optimal policies. Again, are there certain policies that can be selected from the set that are prime candidates? Some such policies are any Pareto policy such that $z^1 = z^2$. Of these, the one where $z^1 + z^2 = 1/2(z_n^{1*}(x) + z_n^{2*}(x))$ is a reasonable policy. Corollary 3.3 relates the three policies that I have been concerned with--the equitable policy, the policy that minimizes the maximum regret, and the policy that minimizes the total regret.

Corollary 3.3 Let z be the Pareto optimal policy related to the weighting $\lambda = 1/2$. Then:

- i) z minimizes the maximum regret,
- ii) z minimizes the total regret.

□

Again, a single policy has all three characteristics, which would make it a good starting point for any further debate.

It might be suspected that theorem 3.3 and corollary 3.3 do not depend on the assumption $j = k = 2$. Corollary 3.4 states that this is in fact so.

Corollary 3.4 If in theorem 3.3 (corollary 3.3) all the assumptions are valid except $k > 2$; $k \geq j \geq 2$, and let $z_n^{1*}(x)$, $z_n^{2*}(x)$ be respectively the minimum and maximum of the k single objective policy function, then the theorem (corollary) is true as stated.

□

Theorem 3.3 is probably more appropriate for controlling several user groups, than for allocating catch to individual boats. If allocation is being done between boats, the upper limit would not be x_t , the initial population size, but rather a series of constraints that depend on the boat capacities. However, the proof of theorem 3.3 depends only on concavity assumptions and simple upper and lower bounds. When allocating between boats there is a similar result, which modifies theorem 3.3 depending on whether the single objective optimal policy

functions are being constrained by the capacity of the boat (i.e., the boat would like to catch more but cannot) or that the optimal catch is at some other level. In this instance, there may be Pareto optimal policies where each (some) boats may catch their total capacity.

Fishery management is often based on fishing effort rather than on catch (see Beverton and Holt 1957; or Rothschild 1972 for a discussion and definitions of fishing effort). However, for many problems this distinction is more apparent than real. I consider the case where the fishing effort of the j users in period t , $e_t = (e_t^1, \dots, e_t^j)$ is normalized by what is usually called a "catchability coefficient," so that they lie in $[0, 1]$ and are additive. Moreover, assume the return to each user can be expressed as a function of the catch to each user, g^k , $k = 1, \dots, j$ and that:

(v) each g^i satisfies assumptions (i) - (iii) as a function of the catch to user i

(vi) total catch is a function of effort through total effort only.

(vii) catch to each user is proportional to:

$$\frac{e^i}{\sum_{\ell=1}^k e^\ell} \cdot (\text{total catch})$$

(viii) total catch is a continuous function of effort, nondecreasing in initial population size x for fixed effort, and nondecreasing in total effort for fixed initial population size.

Assumptions (v) - (viii) relating catch to effort satisfy most of the standard catch and effort models, such as in Anderson (1975) or Ricker (1975). To solve the effort allocation model, I show that it is

only necessary to show that any feasible catch allocation has a related feasible effort allocation. Otherwise, assumption (v) assures that the problems are the same.

Let z^1, z^2 be the allocated catch. Then it is necessary that:

$$\frac{e_1}{e_1 + e_2} (\text{total catch at } e_1, e_2) = z^1$$

$$\frac{e_2}{e_1 + e_2} (\text{total catch at } e_1, e_2) = z^2$$

Let $w^1 = e^1$, and $w^2 = e^1 + e^2$. Then by assumption (vi) total catch is a function of w^2 only, call it $TC(w^2)$. Thus given total catch, total effort is fixed also. The equations become

$$\frac{w_1}{w_2} (TC(w^2)) = z^1$$

$$1 - \frac{w_1}{w_2} (TC(w^2)) = z^2$$

$$TC(w^2), w^2 \text{ fixed; } z^1 + z^2 = TC(w^2)$$

This implies:

$$w^1 = z^2 \left(\frac{w^2}{TC(w^2)} \right) = \left(TC(w^2) - z^1 \right) \left(\frac{w^2}{TC(w^2)} \right).$$

since $z^2 + z^1 = TC(w^2)$ it implies:

$$w^1 = z^2 \left(\frac{w^2}{z^1 + z^2} \right) = z^2 \left(\frac{w^2}{z^1 + z^2} \right)$$

so that any feasible allocation (z^1, z^2) has a related, feasible allocation (w^1, w^2) (or (e^1, e^2)). Thus if assumption (v) - (viii) are valid, solving the catch allocation model solves the effort allocation model.

Other problems certainly can be approached this way. The proofs depend on concavity assumptions, simple constraints (upper and lower bounds) and the recursive formulation of the vector maximization problem: It should be no problem to analyze in a similar manner, for example, the problem where unit price is a function of total catch, so that the return is

$$p^i(\sum_i z^i) \cdot z^i$$

where p^i is a continuous, nonincreasing function, by using dynamic programming to first find the optimal total and then to find the optimal allocation. Other extensions are clearly desirable and I hope to follow up on them in a later paper.

IV. Discussion

The models discussed in this paper are simplifications of any true fishery. While this may be so, for many fisheries, the data does not exist to completely estimate even the models discussed here. Random variation in fish stocks is just beginning to be analyzed, and represents a significant change in our thinking, and hopefully in our policies. The results presented here should be used first and foremost to gain insight and knowledge in determining an optimal policy. It may happen, that after reflection and scrutiny, the calculated policy is used as the actual policy--but I believe this reflection and scrutiny based on our past experience and knowledge cannot be dispensed with.

The results presented here serve another purpose also. Though the exact numbers might be off, they focus the essential areas of conflict in settings relevant to the councils and the FCMA. Too often such bodies spend a lot of time on unfocused debate on points which while their objectives might differ, do not affect policy in any significant way. By pinpointing the crucial areas where policy is in conflict, and by suggesting several reasonable policies to consider at a first pass, Pareto optimal policies provide a focused starting point for council deliberations on OY.

The results here are encouraging in that finding the set of Pareto optimal policies are no more difficult than solving the single-objective optimization problems. While we cannot expect such simple results as our models for fishery management become more complex, the fact that the highly-structured nature of optimal policies is retained in the vector maximum problem, and that the known policies help determined the Pareto policies bodes well for future research in this area. In a subsequent paper, similar techniques will be used to analyze problems where harvesting gain is traded off against increased risk of undesirable events.

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APPENDIX

This Appendix contains the proofs of the various theorems. When there are two separate theorems for $k = 2$ and $k \geq 2$ they are proven together.

Some additional notation is needed. Let $V_t(\delta|H_t)$ be the (vector) expected value of following a policy δ given the history H_t up to time t . Equivalent to maximizing the weighted sum:

$$\sum_{t=1}^T \alpha^{t-1} (\sum_i \lambda^i g^i(x_t, z_t))$$

is a dynamic programming problem given by:

$$f_0^\lambda(\cdot) \equiv 0$$

$$f_n^\lambda(x) = \max \left\{ \sum_i \lambda^i g^i(x, z) + \alpha E f_{n-1}^\lambda(s[x - \sum_i z^i, d]) \right\}$$

where $f_n^\lambda(\cdot)$ denotes the dependence on a fixed value of λ .

Finally, I assume the k single objective policy functions

$z_n^1(x), z_n^2(x), \dots, z_n^k(x)$ are known. For discussion purposes, I assume for fixed x , z_n^1 is the minimum of these k numbers and z_n^2 is the maximum of the k numbers. Associate with these are a dynamic programming problem denoted by

$$f_n^1(x), f_n^2(x) \text{ respectively, for each } n.$$

Theorem 2.1 Part (i). At period t , the value of the history vector H_t is a constant, call it w . Let δ be a dominated policy from period t onwards, and δ^1 an efficient policy. Then the total expected value at period 1 following the different policies is:

$$V_t(\delta^1|H_t) + w; V_t(\delta|H_t) + w$$

The difference is $V_t(\delta^1|H_t) - V_t(\delta|H_t) \geq 0$, so no nonefficient policy from period t onward can be efficient at period one.

Part (ii) is proven by a simple inductive proof, using part (i) and the independence of $D_1, \dots, D_T$ to show that:

$$V_t(\delta|H_t) = V_t(\delta|x_t)$$

□

Corollary 2.1 Immediate consequence of theorem 2.1 and standard dynamic programming arguments.

□

Note that in corollary 2.1 the theorem is to follow some, not any, Pareto optimal policy. Therefore, in checking efficiency of some decision z , it must be tried with all possible values of f_{n-1}^{eff} before ruling it out as dominated. However, if z can be shown to be efficient at period n by some other means, then it is Pareto optimal to choose any efficient policy in period $n-1$.

Lemma A is a restatement of a well known theorem. A proof can be found in Kuhn and Tucker (1951), or Karlin (1959) or Geoffrion (1967).

Lemma A Let G map a subset of R^j into R^k , $k \geq j$, with component function g^i , $i = 1, \dots, k$. If each g^i is concave, and the constraints satisfy the Kuhn-Tucker constraint qualifications, then the following are equivalent:

- (i) $z^+ \in R^j$ is a solution to $\text{vmax } G$
- (ii) $z^+ \in R^j$ is a solution to:

$$\begin{aligned} \max \quad & \sum_{i=1}^k \lambda^i g^i \\ \text{s.t.} \quad & \sum_{i=1}^k \lambda^i = 1; \quad 0 \leq \lambda^i \leq 1 \text{ for all } i \end{aligned}$$

for some value of $\underline{\lambda} = (\lambda^1, \dots, \lambda^k)$.

□

For what follows, I assume that the single objective policy functions exist, and that at least one Pareto optimal policy exists. Given assumptions (i)-(iv) and the convexity of the set C , this is a very mild assumption.

Theorem 3.1 To prove the theorem, it is sufficient to prove part (i), as part (ii) follows from part (i) and theorem 2.1

Part (i) is proven for $k = 2$. For $k > 2$, assume it is true for $i = k-1$. Combine $k-1$ of the objective functions into one. This new objective function satisfies assumptions (i) - Iiii). Moreover, by induction, its optimal policy function for each x and n must lie between the largest and smallest of the $k-1$ single objective optimal policy functions. The result for $i = 2$ then proves the result for $i = k$.

It is convenient to use instead of λ , $1-\lambda$ as the weighting, to use instead 1, $\frac{1-\lambda}{\lambda}$ as the weights, where $\frac{1}{0}$ as a weight implies it is the sole objective considered. Let $u = \frac{1-\lambda}{\lambda}$ on $[0, \infty]$. Each objective obtains its highest expected return at one of the extremes. Therefore, it is sufficient to show that the optimal z is monotone and continuously varying (when it changes) as a function u . However, the monotonicity follows from lemma 7 in Geoffrion (1967) since our "overall utility" is trivially quasiconcave, V_n is concave, and the upper and lower bounds on z are constant as z varies. □

Theorem 3.2 The equivalence of the equitable and minimum total regret policies can be seen from the equivalence of minimizing total regret to:

$$\max_{\delta} \sum_i V_n^i(\delta|x).$$

However, the equitable policy by definition is the policy which maximizes the total even-weighted expected value.

The equivalence with the Chebyshev optimal policy follows from Zangwill (1967). Zangwill proves that if the k function g^i , $i = 1, \dots, k$ are concave, then necessary and sufficient conditions for a Chebyshev optimum are:

$$\sum_{i=1}^k \nabla g^i(x) \cdot w^i = 0 \quad w^i \geq 0$$

$$\sum_i w^i > 0$$

For the problem of this theorem, these are equivalent to the Kuhn-Tucker conditions for even weighting of the k objectives, which proves the equivalence of the Chebyshev optimal and equitable policies

Theorem 3.3 This theorem is proven using a result of Karush (1959), successfully used by Veinott (1966). I assume the problem has a unique solution for each λ . Let $w^1 = z^1$, $w^2 = z^2$, ..., $w^j = \sum_{i=1}^j z^i$. Consider $J_n^\lambda(x, z)$, and substitute in for z . Then:

$$f_n^\lambda(x) = \max_{\substack{0 \leq w^1 \leq w^2 \\ w^2 \leq w^3 \leq w^4 \\ \vdots \\ w^{k-1} \leq w^k \leq x}} \left\{ \sum_{i=1}^k \lambda^i g^i(w^{i+1} - w^i) + \alpha E f_{n-1}^\lambda(s[x - w^k, d]) \right\}$$

The desired result is to show that the problem can be divided into a dynamic recursion involving only w^k , and a simple, static allocation problem given w^k . The proof is for $k = 2$. The proof $k > 2$ is by inducting on k . Assume the theorem is true at $k-1$. Combine the $k-1$ objectives into one single objective (weighted combination when appropriate). Then the result at $k = 2$ implies the result at k .

For fixed (λ, w^2) , let $A(w^2)$ be the solution to:

$$\max_{w^2 \geq w^1 \geq 0} \lambda g^2(w^2 - w^1) + (1 - \lambda) g^1(w^1)$$

Then the total return is $\lambda g^2(w^2 - A(w^2)) + (1 - \lambda) g^1(A(w^2))$ which is a function solely of w^2 . The dynamic recursion then is:

$$f_n^\lambda(x) = \max_{0 \leq w^2 \leq x} \left\{ \lambda g^2(w^2 - A(w^2)) + (1 - \lambda) g^1(A(w^2)) + \alpha E f_{n-1}^\lambda(s[x - w^2, d]) \right\}$$

which depends only on w^2 . Thus, given any w^2 in period n , the value of w^1 (ignoring the trivial case $\lambda = 0$ or 1) is either zero, w^2 or the point where:

$$\lambda g^{2'}(w^2 - w^1) = (1 - \lambda) g^{1'}(w^1)$$

which proves part (ii) of the theorem.

Again, change the weightings by allowing the first objective to be weighted by 1, and the second objective by $\frac{1-\lambda}{\lambda}$. As in theorem 3.1, it is sufficient to show that an optimal w^2 is monotone in u in order to prove the theorem.

As an induction hypothesis, assume $\frac{\partial}{\partial u} J_n^{u[2]}(x, w^2)$ is nondecreasing for $w^2 \leq z_n^2(x)$. At period 2:

$$\frac{\partial}{\partial u} J_2^{u[2]}(x, w^2) = g^{2'}(w^2) - \alpha E(g^{2'}(s[x - w^2, d])s^{[1]}[x - w^2, d])$$

so that the hypothesis is trivially true at period 2. This implies:

$$\frac{\partial}{\partial u} f_2^{u'}(x) = g^{2'}(w_2^2(x))$$

unless $z_2(x)$ is at the boundary, so that since $z_2(x)$ increases with u , $\frac{\partial}{\partial u} f_2^{u'}$ is decreasing in u .

At period n :

$$\frac{\partial}{\partial u} J_n^{u[2]}(x, w^2) = g^{2'}(w^2) - \frac{\partial}{\partial u} \alpha E \left\{ f_{n-1}^{u'}(s[x - w^2, d])s^{[1]}[x - w^2, d] \right\}$$

The second term is decreasing in u , which implies that an optimal w^2 must increase with u , which in turn implies that $\frac{\partial}{\partial u} J_n^{u[2]}(x, w^2)$ is nondecreasing for $w^2 \leq z_n^2(x)$.

To complete the induction, unless the optimal z is x ,

$$\frac{\partial}{\partial u} f_n^{u'}(x) = g^{2'}(w_n^2(x)) \text{ which again decreases with } u.$$

Theorem 3.4 The equivalence of the minimum total regret and the equitable policies is implied by the fact that minimizing total regret is the same as maximizing total unweighted return. Theorem 3.3 implies that the result can be put in terms of a single decision variable w^2 , and the expected return to each objective is (for $k = 2$):

$$\begin{aligned} E \sum_{t=1}^T \alpha^{t-1} g^1(A(w_t^2)) &= E \sum_{t=1}^T \alpha^{t-1} J^1(w_t^2) \\ E \sum_{t=1}^T \alpha^{t-1} g^2(w_t^2 - A(w_t^2)) &= E \sum_{t=1}^T \alpha^{t-1} J^2(w_t^2) \end{aligned}$$

Thus we are back in the one decision variable case as in theorem 3.2, which implies the equivalence of the minimize the maximum regret policy.

□

GLOSSARY AND NOTATION

- FCMA - The Fishery Conservation and Management Act of 1976
(Public Law 94-265)
- OY - optimum yield
- T - the number of period in the planning horizon
- t - subscripts the period
- n - equal to $T - t + 1$, subscripts the number of periods remaining
in the planning horizon
- x_t - stock size at the beginning of period t
- z_t^i - harvest of user i during period t
- z_t - $(z_t^1, \dots, z_t^j)$
- j - number of users
- k - number of total objective functions, $k \geq j$
- $g^i(x, z)$ - one period return to user i given (x, z)
- $G(x, z)$ - $(g^1(x, z), \dots, g^k(x, z))$
- D_t - independent random variable distributed as generic random
variable D
- e_t^i - fishing effort of user i
- e_t - $(e_t^1, \dots, e_t^j)$
- E - conditional expectation
- $s[x - \sum_{i=1}^j z_t^i, D_t]$ - population dynamics (transition function) with
catch as decision variable
- $s[x, E, D_t]$ - transition function when effort is decision
variable

- H_t - the history up to period t (a feasible sequence of states and decisions)
- $vmax$ - vector maximization (efficient set solutions)
- $f_n^{eff}(x)$ - expected vector-value of following some efficient policy from period n onwards when the state is x
- f' - derivative
- ∇f - gradient, with elements $\nabla^i f$
- $f^{[i]}$ - gradient with respect to the i^{th} vector argument
- α - discount factor; $0 < \alpha \leq 1$
- X - set of all possible states
- C - set of possible states and decisions, i.e.
- $$C = \{(x, z) : x \in X; \sum_i z^i \leq x, z^i \geq 0\}$$
- $z_n^{i+}(x)$ - optimal policy function in period n for objective i when it is the sole objective, $i = 1, \dots, k$
- $e_n^{i+}(x)$ - optimal effort policy function for objective i , $i = 1, \dots, k$
- $V_t(\delta | H_t)$ - the vector of expected values in period t of following policy δ given the history is A_t
- $f_n^\lambda(x)$ - total expected value of an optimal policy in period n , given state x , and a convex combination of the k objectives given by λ
- $I_n(\lambda)$ - $f_n^\lambda(x)$ as a function of λ
- $f_n^i(x)$ - total expected value of an optimal policy in period n , given state x , when objective i is the sole objective
- w^i - either $\sum_{k=1}^i z^i$ or $\sum_{k=1}^i e^i$ depending on the context.

THE LINEAR VECTOR MAXIMIZATION PROBLEM AND
MULTIOBJECTIVE MARKOV DECISION PROCESSES

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DRAFT FOR COMMENT

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Markov decision processes have been studied extensively (see Howard 1960; Manne 1960; Denardo 1968, 1977, for example) due to the ability of generally available programming procedures, such as linear programming, to solve a wide class of problems.^{1/} These models consider finite state models, with states 1, 2, ..., N; observed at equally spaced epochs. Associated with each state i is a non-empty decision set D_i . Whenever a state i is observed, some decision $k \in D_i$ must be chosen. Reward R_i^k is received immediately, and a transition is made with probability P_{ij}^k . It is assumed that $\sum_{j=1}^N P_{ij}^k = 1$ for all i, k , so that the matrix P^k is stochastic. Assume also that P^k has only one ergodic chain (Denardo 1977 shows how to relax this assumption). Let V^n be the value of following some stationary policy. Then it is well known that:

$$V^n = ng + w + o(1) \quad \text{as} \quad n \rightarrow \infty$$

It is assumed that it is desired to optimize g , the gain, and then out of all gain-optimal policies, choose the one that has the largest bias w . Let Δ be the set of all stationary policies. Then:

$$g^* = \max \{g^\delta \mid \delta \in \Delta\}$$

$$w_i^* = \max \{w_i^\delta \mid \delta \in \Delta, g^\delta = g^*\} \quad i = 1, \dots, N$$

It is proven in Manne (1960) or Denardo (1977) that a gain-optimal stationary policy must satisfy the following linear program:

^{1/}The notation and discussion on Markov decision problems follows Denardo (1977).

Minimize g

subject to:

Program (1)

$$g + z_i - \sum_j P_{ij}^k z_j \geq R_i^k \quad \text{all } i, k$$

$$g, z_i \text{ unrestricted}$$

or equivalently the dual program:

$$\text{Maximize } \sum_i \sum_k x_i^k R_i^k$$

subject to:

Program (2)

$$\sum_i \sum_k x_i^k = 1$$

$$\sum_k x_i^k - \sum_j \sum_k x_j^k P_{ij}^k = 0 \quad i = 2, \dots, N$$

$$x_i^k \geq 0 \quad \text{all } i, k$$

Suppose instead of one reward each period, we are concerned about a vector of rewards $R_i^k = (R_{i,1}^k, \dots, R_{i,j}^k)$, while retaining the rest of the model as described. We consider again only stationary policies. Sobel (1977) proves that an ordinal sequential game possesses an undominated solution amongst stationary policies if it has one at all. Restricting ourselves to stationary policies is thus reasonable, and in many applications for infinite horizon problems stationary policies are the real policies of interest. Arguing as before, it is true for each objective ℓ , $1 \leq \ell \leq j$, that the total expected value of each stationary policy satisfies

$$v_\ell^n = ng_\ell + w_\ell + o(1)$$

Therefore, for each objective, its gain-optimal policy satisfies programs (1) or (2). Denote the constraints in each of these programs, for each objective ℓ , as C_ℓ^1, C_ℓ^2 .

Let $J^1(x), \dots, J^j(x)$ be functions mapping a subset of $\mathbb{R}^j$ into $\mathbb{R}$ for $x \in X$, and let $J(x) = (J^1(x), \dots, J^j(x))$. Let Ω be the set of feasible values of $J(x)$. Then a particular value of $J(x)$, say J^* , is undominated if there is no feasible $J(x)$ such that

$$J(x) \geq J^* \quad \underline{2/}$$

Let Λ be the set of $J(x)$'s that are undominated, and let C be the corresponding subset of X . The operator vmax maps Ω into Λ , that is $\text{vmax } J(x)$ maps the set of feasible returns into the set of undominated returns. At times I use the slightly abused notation that $\text{vmax } J(x)$ maps X into C , that is it maps the set of feasible solutions into the set of undominated solutions.

If each J^i is a linear function and X is a convex polyhedron, then the problem is often called the linear vector maximization problem (see Evans and Steuer 1973; Yu 1974; Zeleny 1974). Each stationary policy δ produces a vector gain

$$g^\delta = (g_1^\delta, \dots, g_j^\delta)$$

We desire the set of policies δ that satisfies:

$$\text{vmax } g^\delta$$

2/When comparing two j -vectors: $x \geq y$ implies $x^i \geq y^i$ for all i ; $x \geq y$ implies $x^i \geq y^i$ and $x \neq y$; $x > y$ implies $x^i > y^i$ for all i .

However, this is clearly equivalent to:

$$\begin{aligned} & \text{vmin } g \\ & \text{subject to } c_{\ell}^1 \quad \ell = 1, \dots, j \end{aligned} \quad (H_a)$$

or equivalently:

$$\begin{aligned} & \text{vmax } (\sum_i \sum_k x_{ik}^k R_{i,1}^k, \dots, \sum_i \sum_k x_{ik}^k R_{i,j}^k) \\ & \text{subject to } c_{\ell}^2 \quad \ell = 1, \dots, j \end{aligned} \quad (H_b)$$

The two programming problems H_a or H_b reduce the multi-objective Markov decision process to a linear vector maximization problem. For calculating actual efficient sets, this is a significant result, since what progress has been made for developing algorithms for multiobjective problems, has been made in the area of linear problems (see Evans and Steuer 1973; Yu 1974; Zeleny 1974; Benson 1976; Lin 1976 for example). As these algorithms become more efficient, it should be possible to calculate efficient sets for quite general multiobjective Markov decision processes.

II. Discretizing Multiobjective Dynamic Programs

A more common situation, particularly in fields of my interest (fisheries) is that there are j objective functions, which are continuous functions of a state that is contained in a compact subset of Euclidean space, and a continuous random transition function. Assume we can restrict ourselves in the infinite model to stationary policies (again, conditions that insure that the Pareto optimal policy is stationary can be found in Sobel 1977). Also assume that in the infinite model we are willing to discretize the state space, so that the return functions become piecewise

linear. It is well known for the single objective case (see for example Sobel 1971) that this discretization leaves the original problem equivalent to a Markov decision model, and the corresponding linear program is obtained as in the last section, with $R_{i,\ell}^k$ being the value of the return function J_ℓ at state i . Thus it is at least theoretically possible to calculate the set of Pareto optimal stationary policies for a wide class of problems. Given other special structure in the problems (such as being "separable" as in Denardo 1968) it may be possible to reduce the resulting linear vector maximization problems to the point where they are of solvable dimensions.

I hope to explore these possibilities in a later paper, using applications that arise from managing fisheries under the Fishery Conservation and Management Act of 1976.

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A COMPARISON OF METHODS FOR ESTIMATING
AGE-SPECIFIC FISHING MORTALITY RATES
FROM CATCH-AT-AGE DATA

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INTRODUCTION

In an earlier paper (Wetherall and Yong 1975)² we presented results of a first-cut cohort analysis and yield per recruit assessment of the North Pacific albacore, Thunnus alalunga, population. We regarded these results as strictly provisional, and pointed out that several key assumptions needed to be tested and verified. Among these were:

(1) The albacore catch histories, as derived from the catch and length composition statistics and a particular age-length relation, were reasonably accurate. The catch histories may be significantly altered if new information becomes available concerning length composition of catches, particularly catches south of 25°N. Further, the cohort analysis may yield different results if ages are assigned in another manner; for example, by separation of modal length groups (which allows for variation in birth date and growth rate for each cohort) rather than by application of a common length-age relationship (which allows for variation in birth date, but assumes a constant growth pattern for each cohort).

²Wetherall, J. A., and M. Y. Y. Yong. 1975. A cohort analysis of the North Pacific albacore stock and an assessment of yield per recruit in the American and Japanese fisheries. Working paper for the North Pacific albacore population dynamics workshop, December 1975. SWFC Admin. Rep. 16H, 1975, 55 p. 19 tables, 36 figs. Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA, Honolulu, HI 96812.

(2) A second major assumption was that natural mortality coefficients used in the cohort analysis were approximately correct. Considering the difficulties in estimating natural mortality rates, this assumption will likely have to stand unverified, although the robustness of the cohort analysis and other assessments to departures from our assumed conditions should be studied.

(3) A third critical assumption was that the fishing mortality rates on 10-year old albacore during the 4th quarter of each year, 1959-72, were known, or rather that our guesses of these parameters were accurate. In the reverse iterative solution of the catch equation, the sequence of age-specific fishing mortality coefficients is scaled by the value we assign to the fishing mortality rate on this oldest age group, F_n . Error in our guesstimate of F_n leads to biased estimates of F_i , $i = 1, 2, \dots, n-1$. The errors diminish progressively from F_n to F_1 , but in any case the estimate of average fishing mortality rate over the life of each cohort, $\bar{F}$, is biased in the same direction as the error in F_n . To use cohort analysis effectively we therefore need to (a) determine F_n accurately at the outset, or (b) be able to select among alternative values of F_n and their associated sequences of F_i on the basis of independent information, such as tag return statistics. Without an independent and accurate fix on exploitation rate, only the age-specific pattern of fishing mortality may be correctly discerned, and the absolute values of F_i estimates must be viewed cautiously. Further, since we usually must adopt the same estimate of F_n for each cohort, we are severely restricted in drawing inferences about trends in the F_i or in $\bar{F}$ over time.

In the remainder of this paper we set aside the first two major assumptions and focus on the third one. In particular, we wish to compare the usual Gulland-Murphy method of cohort analysis with (a) a newer least squares technique due to Doubleday (1975, 1976), and (b) a simple nonlinear regression method which we developed to estimate parameters of a general age-specific fishing mortality model. After briefly outlining each method, we compare the three techniques using sets of artificially generated catch-at-age data, where the true underlying parameters are known. The parameters, or at least the age-specific patterns, were chosen to mimic approximately the fishery dynamics of North Pacific albacore. Then we apply the three techniques to actual catch-at-age data for the albacore population, as given in our earlier paper.

Outline of Methods

I. Cohort Analysis (Gulland-Murphy Method)

In the reverse iterative solution of the catch equation (Murphy 1964; Gulland 1965), catch-at-age data for each individual cohort (or pooled data from several year classes) are used to yield estimates of the initial cohort size, R , and the age-specific fishing mortality rates for all but the oldest age group (i.e., F_i , $i = 1, 2, \dots, n-1$). The method requires that we specify the age-specific natural mortality coefficients M_i , $i = 1, 2, \dots, n$, and the fishing mortality rate of the oldest age group, F_n .

In this procedure the estimates of F_i depend critically on the fixed value of F_n , and since F_n is usually difficult to establish, the absolute values of the F_i estimates are often questionable, particularly for the older age groups.

II. Doubleday Method

One way to circumvent the problem of having to fix F_n is to reduce the number of other parameters to be estimated. An obvious way to do this is to specify some structure in the age-specific fishing mortality vector, so that different elements are the same or have factors in common. We can then use the same data set to estimate a reduced set of parameters. We avoid having to specify F_n by making the extra structural assumptions. Pope (1974)³ first suggested this could be done by decomposing the fishing mortality rate for the i^{th} age group in the j^{th} fishing period, F_{ij} , into two factors; one representing age-specific effects and another period-specific effects. He suggested the following model:

$$F_{ij} = \exp(s_i + f_j) \quad \begin{array}{l} i = 1, 2, \dots, n \\ j = 1, 2, \dots, m \end{array}$$

where the s_i are assumed constant over time periods and the f_j are constant over age groups.

³Pope, J. G. 1974. A possible alternative method to virtual population analysis for the calculation of fishing mortality from catch at age data. Manuscript for Annu. Meet. Int. Comm. Northwest Atl. Fish. 1974, Res. Doc. No. 20, Serial No. 3166 (mimeogr.)

Doubleday (1976) developed an estimation procedure based on Pope's model which uses the $(m \times n)$ table of the catches, C_{ij} , and a specified constant natural mortality coefficient, M , to produce estimates of $[2(n + m) - 1]$ parameters:

$$(1) \quad s_i \text{ and } f_j \quad i = 1, 2, \dots, n$$

$$j = 1, 2, \dots, m$$

$$\text{and} \quad (2) \quad N_{i,1} \quad i = 1, 2, \dots, n$$

$$N_{1,j} \quad j = 2, 3, \dots, m$$

The latter are estimates of the population sizes for each of the $(m + n - 1)$ year classes at the age when they first enter the catch table.

The estimates are found by an iterative least-squares solution of the nonlinear regression model

$$\begin{aligned} \ln C_{ij} = & \ln \left[\frac{N}{k} \right]_{j-(i-k)} - (i-k)M + (s_i + f_j) \\ & - \sum_{l=k}^{i-1} \exp \left[s_i + f_{j-(i-l)} \right] - \ln \left[\exp(s_i + f_j) + M \right] \\ & + \ln \{ 1 - \exp \left[- \exp(s_i + f_j) - M \right] \} + \epsilon_{ij} \end{aligned}$$

where k is the age at entry to the catch table for the year class from which the catch, C_{ij} , was taken.

Note that the assumption of constant M could be relaxed; we could instead specify values for the individual M_{ij} .

III. Our Regression Method

As Doubleday points out, the Pope model may not be appropriate for many fisheries, particularly those where age-specific factors of fishing mortality vary over time, or equivalently, time-specific factors vary over age. This may well be the case for North Pacific albacore. For example, nominal fishing effort has increased substantially in recent years, but this has been directed more at younger albacore than at the older fish.

We have recently experimented with an alternative approach which involves the estimation of a parametric age-dependent fishing mortality function using catch-at-age data from individual cohorts. Consider the general deterministic catch equation

$$C_i = \int_{t_i}^{t_i + \Delta_i} F(u) R \exp \left\{ - \int_0^u [M(x) + F(x)] dx \right\} du$$

$$= H(t_i + \Delta_i) - H(t_i)$$

where C_i = catch in the i^{th} age interval $(t_i, t_i + \Delta_i)$

t_i = age at beginning of i^{th} interval

Δ_i = length of i^{th} interval

$F(u)$ = instantaneous fishing mortality rate at age u

$M(x)$ = instantaneous natural mortality rate at age x

R = initial cohort size

$H(u)$ = cumulative catch from the cohort at age u

Assume that $M(u) = M = \text{constant}$ and that the differential $dH(u)$ is linear over each age interval, i.e., piecewise linear over the exploited life of the cohort. Under these conditions,

$$C_i = \Delta_i R F(\tau_i) \exp \left[-M\tau_i - \int_0^{\tau_i} f(u) du \right]$$

where $\tau_i = t_i + \Delta_i/2$.

This leads to a general nonlinear regression model

$$\ln(C_i/\Delta_i) = \ln R + \ln F(\tau_i) - M\tau_i - \int_0^{\tau_i} F(u) du + \varepsilon_i \quad (1)$$

where ε_i is a random error term.

To apply this model we need to specify the form of $F(u)$. For example, if we let $F(u) = F = \text{constant}$, the linearity assumption is satisfied and equation 1 reduces to the well-known catch curve model

$$\ln(C_i/\Delta_i) = \ln(RF) - (F + M)\tau_i + \varepsilon_i$$

which may be used to yield a least squares estimate of the total mortality rate, $Z = F + M$, and, if M is specified, estimates of F and R .

Of course, our main concern is to explore more complicated fishing mortality functions, ones for which equation 1 is only an approximation. For many tunas, including North Pacific albacore, cohort analyses suggest a fishing mortality sequence typified by Figure 1.

Fishing mortality rates show an erratic seasonal fluctuation around a basically dome-shaped curve. Because of phase-shifts in the mortality cycles a detailed model of $F(u)$ would likely be quite cumbersome. For

many purposes, we can show that it is sufficient to model only the main underlying trend. Specifically, for North Pacific albacore we examined the model

$$F(u) = \alpha(u + \theta) \exp(-\beta u)$$

which faithfully traces the trend in Figure 1. Substituting in equation 1, we have

$$\begin{aligned} \ln(C_i/\Delta_i) = & \ln(R\alpha) - (\beta + M)\tau_i + \ln(\tau_i + \theta) \\ & - (\alpha/\beta^2) \left\{ 1 - \exp(-\beta\tau_i) - \beta\tau_i \exp(-\beta\tau_i) \right. \\ & \left. + \beta\theta \left(1 - \exp(-\beta\tau_i) \right) \right\} + \epsilon_i \end{aligned} \quad (2)$$

To better isolate fishing mortality we assume M is known, and then estimate just R , θ , α , and β .

We note here that our assumption of constant natural mortality rate, M , was for convenience only. Equations 1 and 2 may be modified if information is available on age-specific M .

COMPARISONS USING ARTIFICIAL DATA

The Generated Data Sets

We generated two sets of deterministic catch-at-age data for use in comparing the three procedures. In each case we specified Pope's age-specific and period-specific components, s_i and f_j , of the age-specific fishing mortality rates, F_{ij} . All rates were computed on a quarterly basis over 20 fishing years. Tables 1 and 2 list the mortality

components for data set D1, in which the rates are constant over all quarters in each year, satisfying the assumptions of Doubleday's method.

Tables 3,4 Tables 3 and 4 give the elemental rates for data set D2, in which the rates vary quarterly. In all cases the catch-at-age data were generated for 8 year-groups (32 quarter-year age groups), with $R = 1,000$ and $M = 0.20$ for each cohort. Example catch data for one fishing year in each data set are shown in Tables 5 and 6. The average annual age-specific fishing mortality rates for each fishing year are given in Table 7 for set D1 and Table 8 for set D2.

The standard cohort analysis and our new regression technique employ individual year-class catch histories. One of these from each data set, D1 and D2, is given in Tables 9 and 10 (picked arbitrarily). The associated age-specific fishing mortality rates from which the selected data were generated are listed in Tables 11 and 12. In Figure 2 we plot the quarterly fishing mortality coefficients for the selected year class in set D1. The rates for the D2 year class are in Figure 3.

Results of Cohort Analysis

Cohort analysis was done on the selected year-class catch histories of sets D1 and D2, using the FORTRAN program COHORT (W. W. Fox, SWFC, La Jolla, California). Natural mortality was set to 0.20 for all ages. The resulting age-specific fishing mortality estimates are given in Figures 4 and 5 for different values of F_n . Both quarterly and

annual catch data were analyzed. In addition, the average fishing mortality rate over the life of each cohort, $\bar{F}$, was computed:

$$\bar{F} = \frac{\sum_{i=1}^n F_i \bar{N}_i}{\sum_{i=1}^n \bar{N}_i} = \frac{\sum_{i=1}^n C_i}{\sum_{i=1}^n \bar{N}_i}$$

where $\bar{N}_i$ is the average size of the cohort during the i^{th} age interval.

The estimates of $\bar{F}$ are also indicated on Figures 4 and 5.

As expected, the actual sequence of F_i is estimated accurately provided F_n is on the mark. Otherwise the estimates of F_i are in error, the error being greater for older age groups.

Results of Analysis Using Doubleday Method

Doubleday's method was applied to the (20 x 8) catch-at-age tables for sets D1 and D2, using the FORTRAN programs POPI and POPO (Doubleday 1975). POPI was used initially with $M = 0.20$, with s_8 set to -1.0 and with all other parameters set to zero. Results of POPI were then input to POPO. POPO was applied repeatedly until convergence was achieved.

le 13 Estimates of the F_{ij} for data set D1 were very accurate;
le 14 compare the POPO output in Table 13 with the actual values of Table 7. On the other hand, estimates of F_{ij} for data set D2 have a fairly large positive bias; compare Table 14 with the true values in Table 8. It is doubtful whether different initial estimates would improve the estimation. The bias probably arises from the failure of Doubleday's basic assumptions

that the age-specific fishing mortality factors are constant over time. However, our conclusion here is not final, and we intend to explore the matter further.

Results of Analysis Using Our Regression Model

The nonlinear regression model at equation 2 was applied to annual (8 data points) and quarterly (32 points) series of data from the selected year-class catch histories, both D1 and D2. Natural mortality was fixed at $M = 0.20$. Figures 6, 7, 8, and 9 show the data and the fitted regression lines. The fit to the annual data is somewhat better than the fit to quarterly data, as expected, especially in case D2.

Table 15

Table 15 gives the parameter estimates $\hat{R}$, $\hat{\theta}$, $\hat{\alpha}$, and $\hat{\beta}$ for each fishing mortality function, and lists the true values of R . In addition the table gives true and estimated values of $\bar{F}$ for each case, where

$$\bar{F} = \int_0^8 F(u) N(u) du / \int_0^8 N(u) du$$

In all cases the initial cohort size, R , is underestimated, and $\bar{F}$ is overestimated except for the annual data of set D2.

Table 16

Table 16 lists the actual average fishing mortality rates during 5 years of each cohort's life, along with the regression function estimates of $\bar{F}$ at the midpoints of those years (based on annual data). The same information is plotted in Figures 10 and 11. The main trends in fishing

Figs. 10,
11

mortality rate are determined fairly accurately by the regression analysis, but the absolute values generally show a positive bias.

ANALYSIS OF ALBACORE CATCH-AT-AGE DATA

We applied ordinary cohort analysis and our new regression method to two sets of North Pacific albacore data:

(1) the catch-at-age data for the 1961 year class (Wetherall and Yong 1975, Table 6), and

(2) an aggregated catch-at-age vector formed by summing individual catch histories for year classes 1957-61.

figs. 12,13

The cohort analysis results are given in Figures 12 and 13.

For the given values of F_n they show a general dome-shaped pattern, with a peak fishing mortality rate at coded age 3 (true age 5). The main problem is to choose among these alternative curves.

Table 17

The average fishing mortality rates, $\bar{F}$, over 8 years of the 1961 year class are also given in Figures 12 and 13. In addition, Table 17 lists the average fishing mortality rates over 8 years for each of the individual cohorts, 1957-61, corresponding to four different levels of F_n , the fishing mortality on 10-year olds during the 4th quarter. An order of magnitude difference in F_n results in a similar difference in $\bar{F}$.

Table 18

The results of our regression analysis are given in Table 18, which lists the estimated parameters and associated $\bar{F}$ for each data set. The actual catch curves and estimated regression lines are shown in

figs. 14,
16,17

Figures 14, 15, 16, and 17.

We found in examining the test data of sets D1-YC10 and D2-YC20 that the regression method gave a fairly close but perhaps positively biased estimate of $\bar{F}$. The estimate was best when derived from annual data. On the other hand, the individual age-specific values of F_i might not be estimated quite so well. With these results in mind, we suggest that the regression method can serve as a guide in selecting a "best" age-specific F-vector from the cohort analyses, based on a comparison of $\bar{F}$ values. In the case of YC-1961 and the aggregate YC-1957-61, we compare Tables 16 and 17. Allowing for the presumed positive bias in $\hat{\bar{F}}$, we judge in both cases that the "best" F-vector would be one associated with an F_n equal to about 0.10.

Tables 16,
17

In addition to using cohort analysis and the regression method on data from YC-1961 and YC-1957-61, we applied POPI and POPO to two sets of North Pacific albacore catch-at-age data; one set covering fishing years 1952-65, another spanning 1959-72. In both cases the estimates of age-specific F seemed to have a serious positive bias, and the residual mean squares were substantially larger than Doubleday (1975) allows for reliable results.

CONCLUSIONS

Our very cursory comparison of methods for estimating age-specific fishing mortality rates has led us to conclude provisionally that Pope's model and Doubleday's method of implementing it are not very robust; the method works when its assumptions are satisfied, but not under the conditions likely to be encountered in the North Pacific albacore fisheries.

On the other hand, our results indicate that a more thorough investigation of our regression method would be fruitful, and we are planning a more complete investigation. We particularly feel that the regression procedure can establish a reasonably accurate estimate of the average fishing mortality rate, $\bar{F}$, over a cohort's life. If so, the method would be very useful in sifting through the vectors of F_i computed in ordinary cohort analysis, and choosing the best one, since there is a direct relationship between the guess of F_n and the resulting estimate of $\bar{F}$.

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Table 1.--Age-specific fishing mortality factors, s_i , for data set D1.

Age interval (years)	s_i	$\exp(-s_i)$
2.5-3.5	-0.693	0.50
3.5-4.5	0.406	1.50
4.5-5.5	0.0	1.00
5.5-6.5	-0.693	0.50
6.5-7.5	-1.609	0.20
7.5-8.5	-2.303	0.10
8.5-9.5	-2.303	0.10
9.5-10.5	-2.995	0.05

Table 2.--Year-specific fishing mortality factors, f_j , for data set D1.

Fishing year	f_j	$\exp(-f_j)$
1	-0.223	0.8
2	-0.223	0.8
3	-0.223	0.8
4	-0.223	0.8
5	-0.223	0.8
6	-0.223	0.8
7	-0.223	0.8
8	-0.223	0.8
9	-0.223	0.8
10	-0.223	0.8
11	0.000	1.0
12	0.182	1.2
13	0.336	1.4
14	0.470	1.6
15	0.588	1.8
16	0.693	2.0
17	0.742	2.1
18	0.876	2.4
19	0.876	2.4
20	0.876	2.4

Table 3.--Quarterly age-specific fishing mortality factors, s_i ,
for data set D2.

Age interval (years)	s_i			
	Quarter 1	Quarter 2	Quarter 3	Quarter 4
2.5-3.5	-3.912	-0.693	-0.223	-1.609
3.5-4.5	-2.303	0.406	-0.916	-1.609
4.5-5.5	-1.609	0.000	-1.609	-1.204
5.5-6.5	-0.916	-0.693	-2.996	-0.916
6.5-7.5	-1.609	-1.609	-4.605	-1.609
7.5-8.5	-2.303	-2.303	$\rightarrow(-\infty)$	-2.303
8.5-9.5	-2.303	-2.303	$\rightarrow(-\infty)$	-2.303
9.5-10.5	-2.303	-2.996	$\rightarrow(-\infty)$	-2.303

Table 4.--Quarterly time-specific fishing mortality factors, f_j ,
for data set D2.

Fishing year	f_j			
	Quarter 1	Quarter 2	Quarter 3	Quarter 4
1	-0.916	-0.223	-0.223	-0.916
2	-0.916	-0.223	-0.223	-0.916
3	-0.916	-0.223	-0.223	-0.916
4	-0.916	-0.223	-0.223	-0.916
5	-0.916	-0.223	-0.223	-0.916
6	-0.916	-0.223	-0.223	-0.916
7	-0.916	-0.223	-0.223	-0.916
8	-0.916	-0.223	-0.223	-0.916
9	-0.916	-0.223	-0.223	-0.916
10	-0.916	-0.223	-0.223	-0.916
11	-0.916	0.000	-0.223	-0.916
12	-0.916	0.182	-0.223	-0.916
13	-0.916	0.336	-0.223	-0.916
14	-0.916	0.470	-0.223	-0.916
15	-0.916	0.588	-0.223	-0.916
16	-0.916	0.693	-0.223	-0.916
17	-0.916	0.788	-0.223	-0.916
18	-0.916	0.876	-0.223	-0.916
19	-0.916	0.876	-0.223	-0.916
20	-0.916	0.876	-0.223	-0.916

Table 5.--Scaled catch-at-age for fishing year 1, data set D1.

Age interval	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Total
2.5-3.5	92.9	79.9	68.8	59.2	300.8
3.5-4.5	138.9	97.9	69.0	48.6	354.4
4.5-5.5	23.9	18.6	14.5	11.3	68.4
5.5-6.5	4.6	4.0	3.4	2.9	14.9
6.5-7.5	1.0	1.0	0.9	0.8	3.7
7.5-8.5	0.4	0.3	0.3	0.3	1.3
8.5-9.5	0.3	0.3	0.2	0.2	1.0
9.5-10.5	0.1	0.1	0.1	0.1	0.4

Table 6.--Scaled catch-at-age for fishing year 1, data set D2.

Age interval	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Total
2.5-3.5	1.9	88.2	117.9	12.8	220.8
3.5-4.5	6.0	147.2	30.7	7.0	190.9
4.5-5.5	6.5	55.4	9.3	6.4	77.6
5.5-6.5	7.9	17.4	1.6	5.8	32.7
6.5-7.5	2.7	5.0	0.2	2.2	10.1
7.5-8.5	1.0	1.9	0.0	0.9	3.8
8.5-9.5	0.8	1.5	0.0	0.7	3.0
9.5-10.5	0.6	0.6	0.0	0.5	1.7

Table 7.--Actual age-specific fishing mortality rates for data set D1.

Fishing year	Age group (midpoint, years)							
	3	4	5	6	7	8	9	10
1	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
2	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
3	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
4	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
5	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
6	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
7	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
8	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
9	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
10	0.40	1.20	0.80	0.40	0.16	0.08	0.08	0.04
11	0.50	1.50	1.00	0.50	0.20	0.10	0.10	0.05
12	0.60	1.80	1.20	0.60	0.24	0.12	0.12	0.06
13	0.70	2.10	1.40	0.70	0.28	0.14	0.14	0.07
14	0.80	2.40	1.60	0.80	0.32	0.16	0.16	0.08
15	0.90	2.70	1.80	0.90	0.36	0.18	0.18	0.09
16	1.00	3.00	2.00	1.00	0.40	0.20	0.20	0.10
17	1.10	3.30	2.20	1.10	0.44	0.22	0.22	0.11
18	1.20	3.60	2.40	1.20	0.48	0.24	0.24	0.12
19	1.20	3.60	2.40	1.20	0.48	0.24	0.24	0.12
20	1.20	3.60	2.40	1.20	0.48	0.24	0.24	0.12

Table 8.--Actual age-specific fishing mortality rates for data set D2.

Fishing year	Age group (midpoint, years)							
	3	4	5	6	7	8	9	10
1	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
2	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
3	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
4	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
5	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
6	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
7	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
8	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
9	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
10	0.27	0.42	0.30	0.19	0.08	0.04	0.04	0.03
11	0.30	0.50	0.35	0.22	0.09	0.04	0.04	0.03
12	0.32	0.60	0.40	0.25	0.10	0.05	0.05	0.04
13	0.35	0.66	0.46	0.27	0.11	0.06	0.06	0.04
14	0.38	0.74	0.51	0.30	0.12	0.06	0.06	0.04
15	0.40	0.82	0.56	0.33	0.14	0.07	0.07	0.04
16	0.43	0.90	0.62	0.35	0.14	0.07	0.07	0.04
17	0.46	0.98	0.67	0.38	0.16	0.08	0.08	0.05
18	0.48	1.06	0.73	0.41	0.17	0.08	0.08	0.05
19	0.48	1.06	0.73	0.41	0.17	0.08	0.08	0.05
20	0.48	1.06	0.73	0.41	0.17	0.08	0.08	0.05

Table 9. ~~Scaled catch-at-age~~ for year-class 10, data set D1.

Age interval	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Total
2.5-3.5	92.9	79.9	68.8	59.2	300.8
3.5-4.5	138.9	97.9	69.0	48.6	354.4
4.5-5.5	23.9	18.6	14.5	11.3	68.4
5.5-6.5	4.6	4.0	3.4	2.9	14.9
6.5-7.5	1.0	1.0	0.9	0.8	3.7
7.5-8.5	0.4	0.3	0.3	0.3	1.3
8.5-9.5	0.3	0.3	0.2	0.2	1.0
9.5-10.5	0.1	0.1	0.1	0.1	0.4

Table 10.--Scaled catch-at-age for year-class 20, data set D2.

Age interval	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Total
2.5-3.5	1.9	148.8	109.4	11.9	272.0
3.5-4.5	5.6	238.0	21.1	4.8	269.5
4.5-5.5	4.4	76.1	5.0	3.4	89.0
5.5-6.5	4.2	21.7	0.7	2.7	29.3
6.5-7.5	1.2	6.1	0.1	0.9	8.3
7.5-8.5	0.4	2.4	0.0	0.4	3.2
8.5-9.5	0.3	1.8	0.0	0.3	2.4
9.5-10.5	0.2	0.7	0.0	0.2	1.1

Table 11.--Age-specific fishing mortality rates for year-class 10,
data set D1.

Age interval	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Average
2.5-3.5	0.40	0.40	0.40	0.40	0.40
3.5-4.5	1.20	1.20	1.20	1.20	1.20
4.5-5.5	0.08	0.08	0.08	0.08	0.08
5.5-6.5	0.40	0.40	0.40	0.40	0.40
6.5-7.5	0.16	0.16	0.16	0.16	0.16
7.5-8.5	0.08	0.08	0.08	0.08	0.08
8.5-9.5	0.08	0.08	0.08	0.08	0.08
9.5-10.5	0.04	0.04	0.04	0.04	0.04

Table 12.--Age-specific fishing mortality rates for year-class 20,
data set D2.

Age interval	Quarter 1	Quarter 2	Quarter 3	Quarter 4	Average
2.5-3.5	0.01	0.70	0.64	0.08	0.35
3.5-4.5	0.04	2.40	0.32	0.08	0.74
4.5-5.5	0.08	1.80	0.16	0.12	0.56
5.5-6.5	0.16	1.00	0.04	0.16	0.35
5.6-7.5	0.08	0.44	0.01	0.08	0.16
7.5-8.5	0.04	0.24	0.00	0.04	0.08
8.5-9.5	0.04	0.24	0.00	0.04	0.08
9.5-10.5	0.04	0.12	0.00	0.04	0.05

Table 13.--Estimates of F_{ij} to year-class 10, data set D1, using
Doubleday's method.

Fishing year	Age group (midpoint, years)							
	3	4	5	6	7	8	9	10
1	0.41	1.22	0.83	0.42	0.17	0.09	0.09	0.04
2	0.41	1.22	0.83	0.42	0.17	0.09	0.09	0.04
3	0.41	1.22	0.83	0.42	0.17	0.09	0.09	0.04
4	0.41	1.22	0.83	0.42	0.17	0.09	0.09	0.04
5	0.40	1.22	0.82	0.42	0.17	0.09	0.08	0.04
6	0.40	1.22	0.82	0.42	0.17	0.09	0.08	0.04
7	0.40	1.22	0.82	0.42	0.17	0.09	0.08	0.04
8	0.40	1.21	0.82	0.42	0.17	0.09	0.08	0.04
9	0.40	1.21	0.82	0.42	0.17	0.08	0.08	0.04
10	0.40	1.21	0.82	0.42	0.17	0.08	0.08	0.04
11	0.50	1.51	1.02	0.52	0.21	0.11	0.11	0.05
12	0.60	1.80	1.22	0.63	0.25	0.13	0.13	0.06
13	0.70	2.11	1.43	0.73	0.30	0.15	0.15	0.07
14	0.80	2.41	1.63	0.84	0.34	0.17	0.17	0.08
15	0.90	2.71	1.83	0.94	0.38	0.19	0.19	0.09
16	1.00	3.01	2.04	1.05	0.42	0.21	0.21	0.10
17	1.10	3.31	2.24	1.15	0.47	0.23	0.23	0.11
18	1.21	3.63	2.46	1.26	0.51	0.25	0.25	0.13
19	1.23	3.69	2.50	1.28	0.52	0.26	0.26	0.13
20	1.19	3.59	2.43	1.25	0.50	0.25	0.25	0.12

Table 14.--Estimates of F_{ij} for year-class 20, data set D2, using
Doubleday's method.

Fishing year	Age group (midpoint, years)							
	3	4	5	6	7	8	9	10
1	0.37	0.70	0.64	0.56	0.32	0.17	0.19	0.14
2	0.37	0.71	0.64	0.56	0.32	0.18	0.19	0.14
3	0.37	0.70	0.64	0.56	0.32	0.17	0.19	0.14
4	0.37	0.70	0.63	0.55	0.31	0.17	0.19	0.14
5	0.36	0.70	0.63	0.55	0.31	0.17	0.19	0.14
6	0.36	0.69	0.63	0.55	0.31	0.17	0.18	0.14
7	0.36	0.69	0.62	0.54	0.31	0.17	0.18	0.13
8	0.35	0.67	0.61	0.53	0.30	0.17	0.18	0.13
9	0.34	0.65	0.59	0.52	0.29	0.16	0.17	0.13
10	0.33	0.63	0.57	0.50	0.28	0.16	0.17	0.12
11	0.35	0.68	0.62	0.54	0.31	0.17	0.18	0.13
12	0.38	0.73	0.66	0.58	0.33	0.18	0.19	0.14
13	0.41	0.78	0.71	0.62	0.35	0.19	0.21	0.15
14	0.44	0.80	0.76	0.67	0.38	0.21	0.22	0.17
15	0.47	0.90	0.81	0.71	0.40	0.22	0.24	0.18
16	0.51	0.97	0.88	0.77	0.44	0.24	0.26	0.19
17	0.55	1.05	0.96	0.84	0.48	0.26	0.28	0.21
18	0.62	1.19	1.08	0.95	0.54	0.30	0.32	0.23
19	0.70	1.34	1.22	1.07	0.61	0.33	0.36	0.26
20	0.90	1.73	1.57	1.37	0.78	0.43	0.46	0.34

Table 15.--Estimates of regression model parameters for cohorts D1-YC10
and D2-YC20, based on annual and quarterly data.

Cohorts	$\hat{R}$	Parameters				Data points
		$\hat{\alpha}$	$\hat{\beta}$	$\hat{\theta}$	$\hat{F}$	
D1-YC10						
Annual data	841	1.588	0.560	0.000	0.66	8
Quarterly data	897	1.502	0.574	0.126	0.72	32
True values	1,000	--	--	--	0.60	--
D2-YC20						
Annual data	751	0.724	0.498	0.189	0.43	8
Quarterly data	348	0.982	0.315	0.000	0.58	32
True values	1,000	--	--	--	0.44	--

Table 16.--Estimated and actual fishing mortality rates for cohorts D1-YC10 and D2-YC20, based on regression analysis of annual data.

Cohorts	Coded age interval	Coded age at midpoint	Actual average F during interval	Estimated F at midpoint
D1-YC10	1	0.5	0.400	0.601
	2	1.5	1.200	1.029
	4	3.5	0.400	0.784
	6	5.5	0.080	0.402
	8	7.5	0.040	0.179
D2-YC20	1	0.5	0.351	0.389
	2	1.5	0.740	0.579
	4	3.5	0.354	0.467
	6	5.5	0.082	0.266
	8	7.5	0.051	0.133

Table 17.--Estimated values of $\bar{F}$ for North Pacific albacore year classes 1957-61, corresponding to different values of F_n .

F_n	Year class				
	1957	1958	1959	1960	1961
0.40	0.52	0.42	0.60	0.49	0.43
0.20	0.44	0.38	0.57	0.44	0.37
0.10	0.34	0.32	0.50	0.35	0.29
0.01	0.07	0.09	0.17	0.08	0.06

Table 18.--Estimates of regression model parameters for two sets of
North Pacific albacore catch-at-age statistics.

Cohorts	Parameters					Data points
	$\hat{R}$	$\hat{\alpha}$	$\hat{\beta}$	$\hat{\theta}$	$\hat{F}$	
YC-1961						
Annual data	998	0.339	0.149	0.276	0.40	8
	1,022	0.150	0.001	0.000	0.24	9
Quarterly data	576	0.380	0.120	0.000	0.38	32
	406	0.146	0.001	0.000	0.24	36
YC-1957-61						
Annual data	837	0.573	0.295	0.000	0.44	8
	793	0.160	0.010	0.000	0.25	9
Quarterly data	506	0.630	0.259	0.000	0.45	32
	384	0.161	0.001	0.000	0.25	36

Figure 1. Sequence of quarterly F_1 for combined catfish histories of all years-classes 1957-61, based on cohort analysis with $F_0 = .10$.

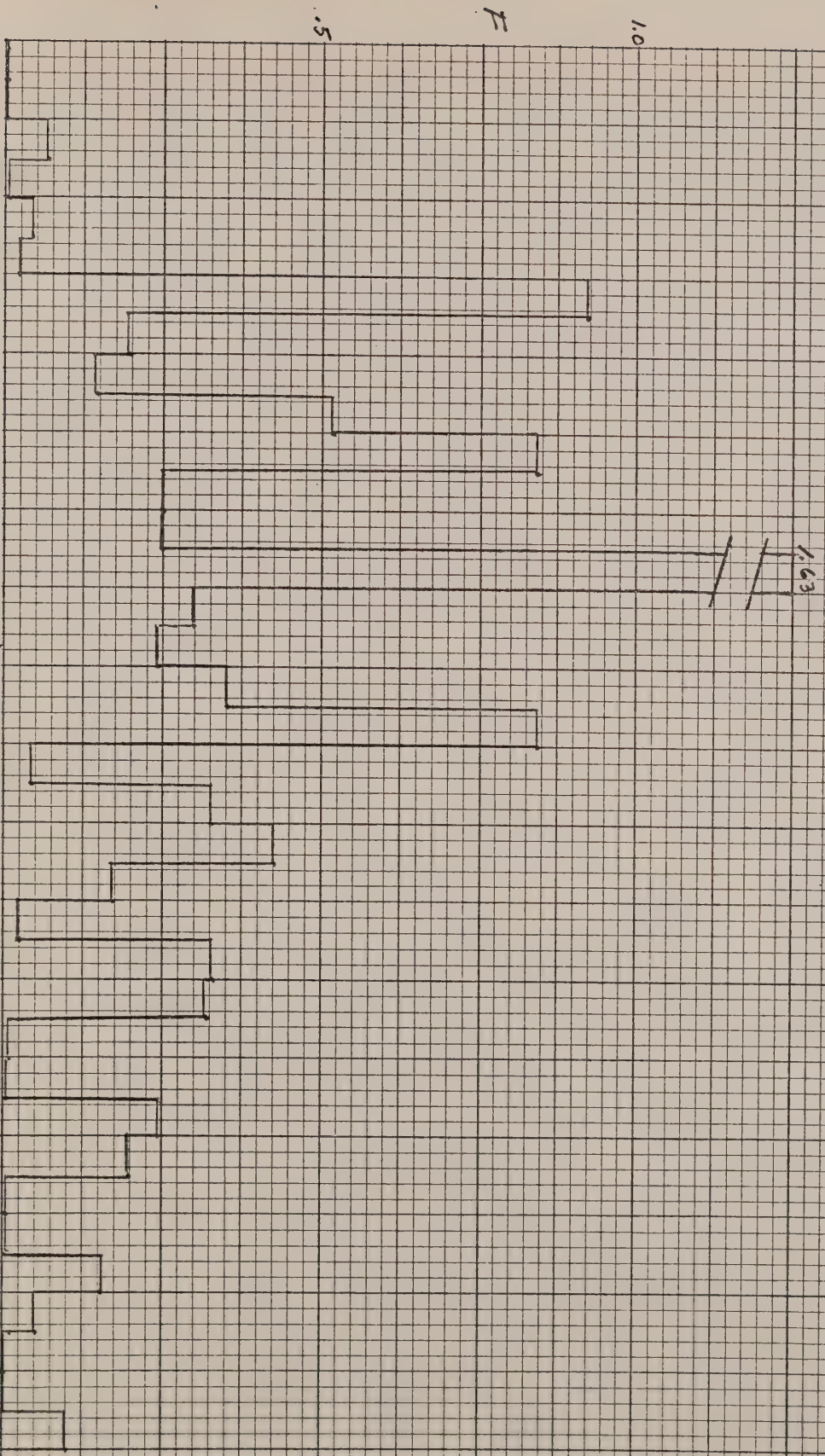


Figure 2. Mean F_1 for D1-YC20, annual.

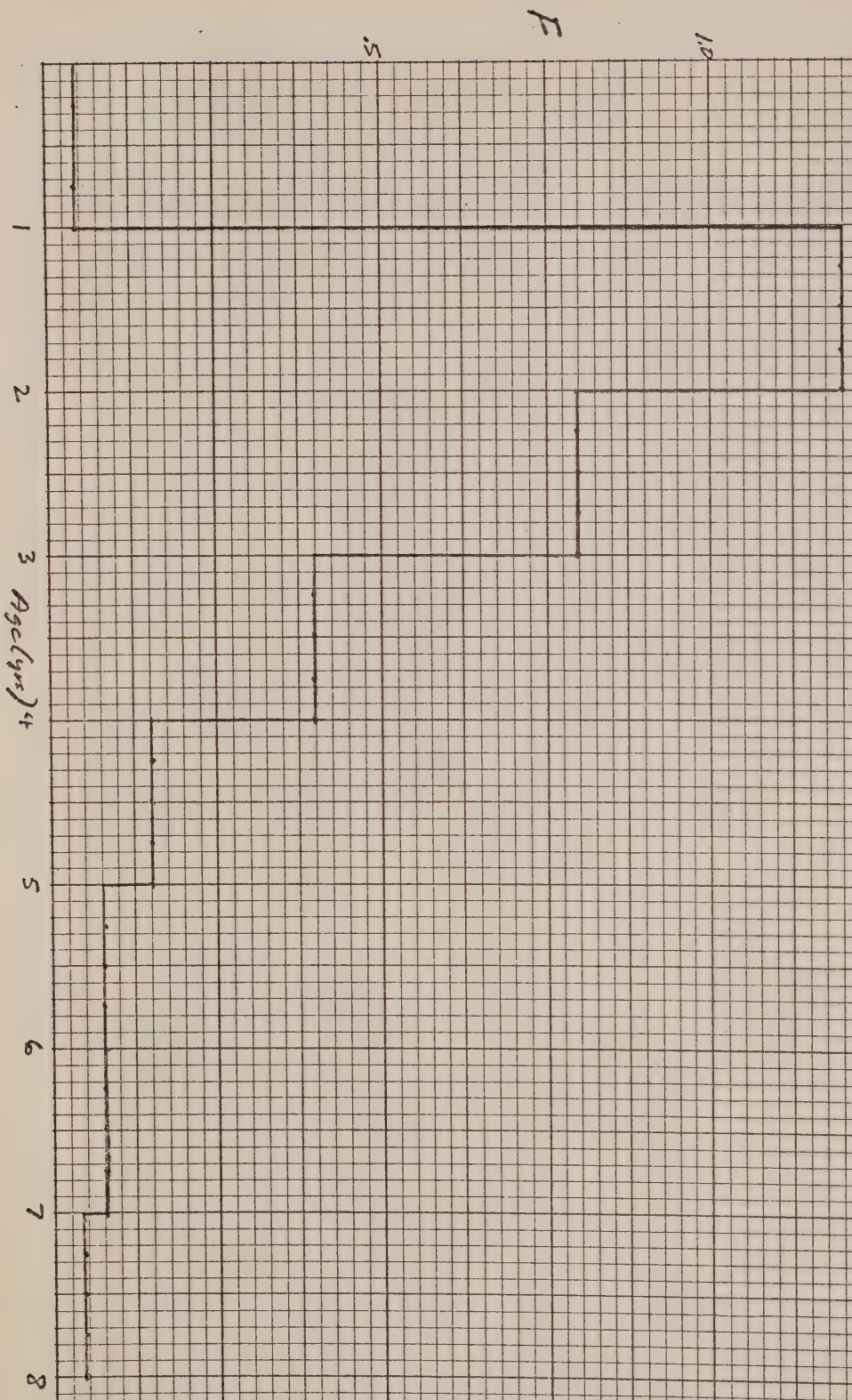


Figure 3. Actual F_0 for DZ-YCZ-0, quarterly.

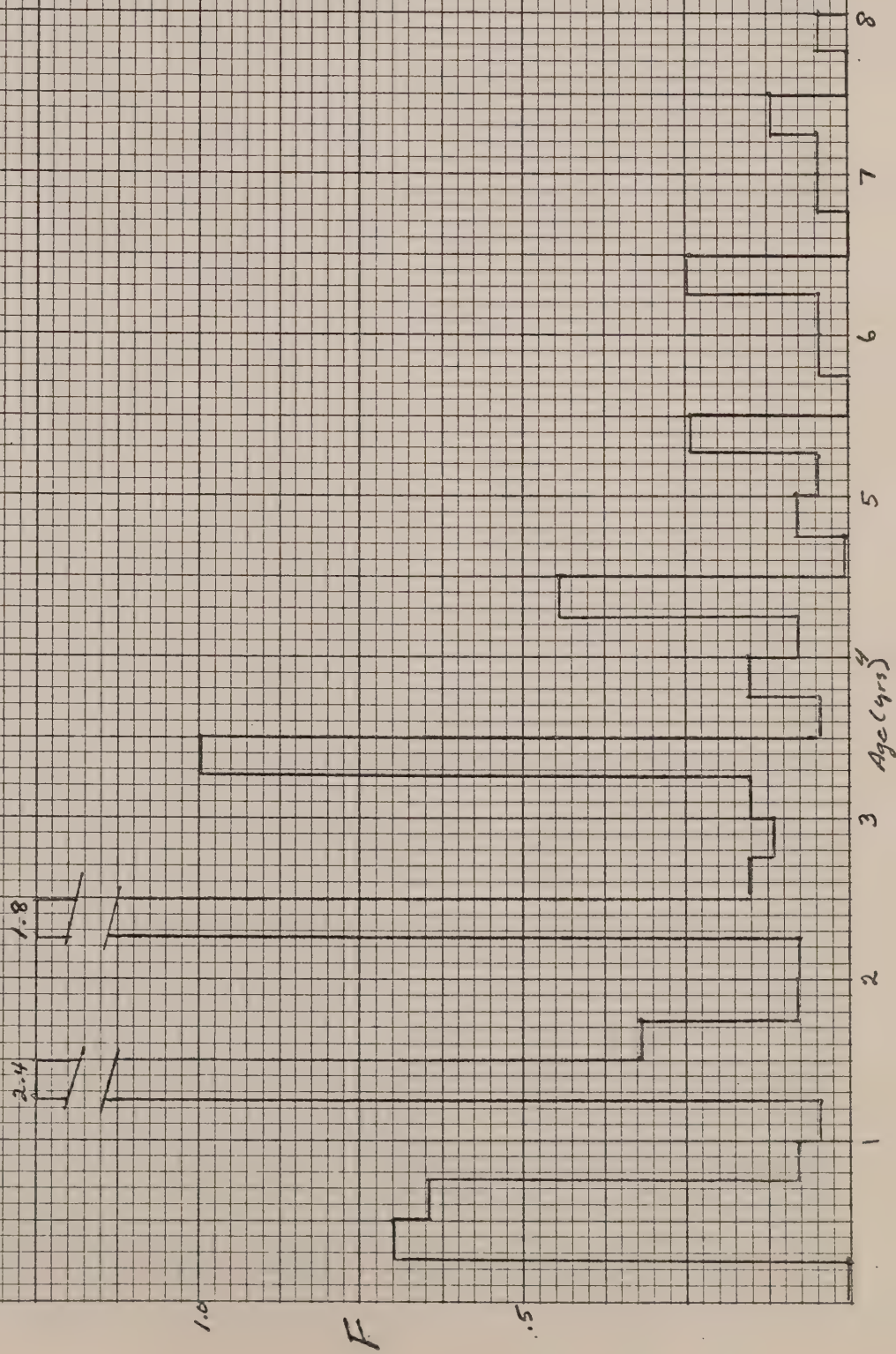


Figure 4a. Cohort analysis estimates of F_i , quarterly,
for DI-YC10

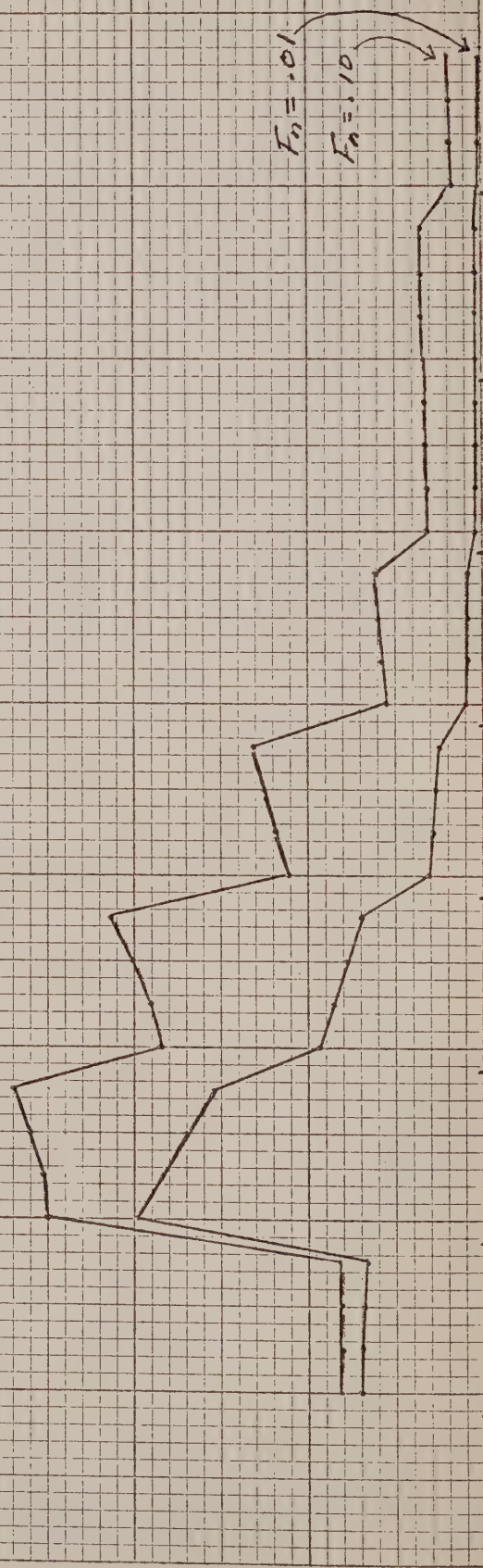


Figure 4b. Cohort analysis estimates of F_t , annually,
for DI-YC10

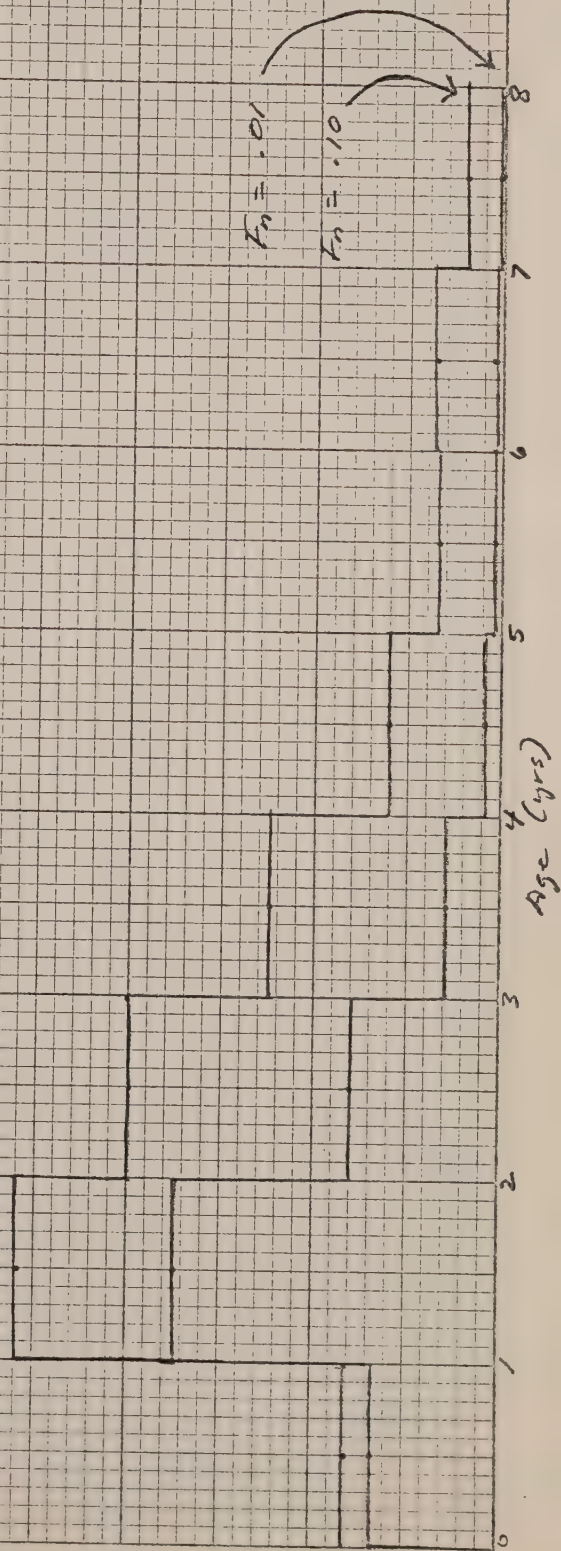


Figure 5a. Cohort analysis estimates of F_i , quarterly,
for D2-XC20.

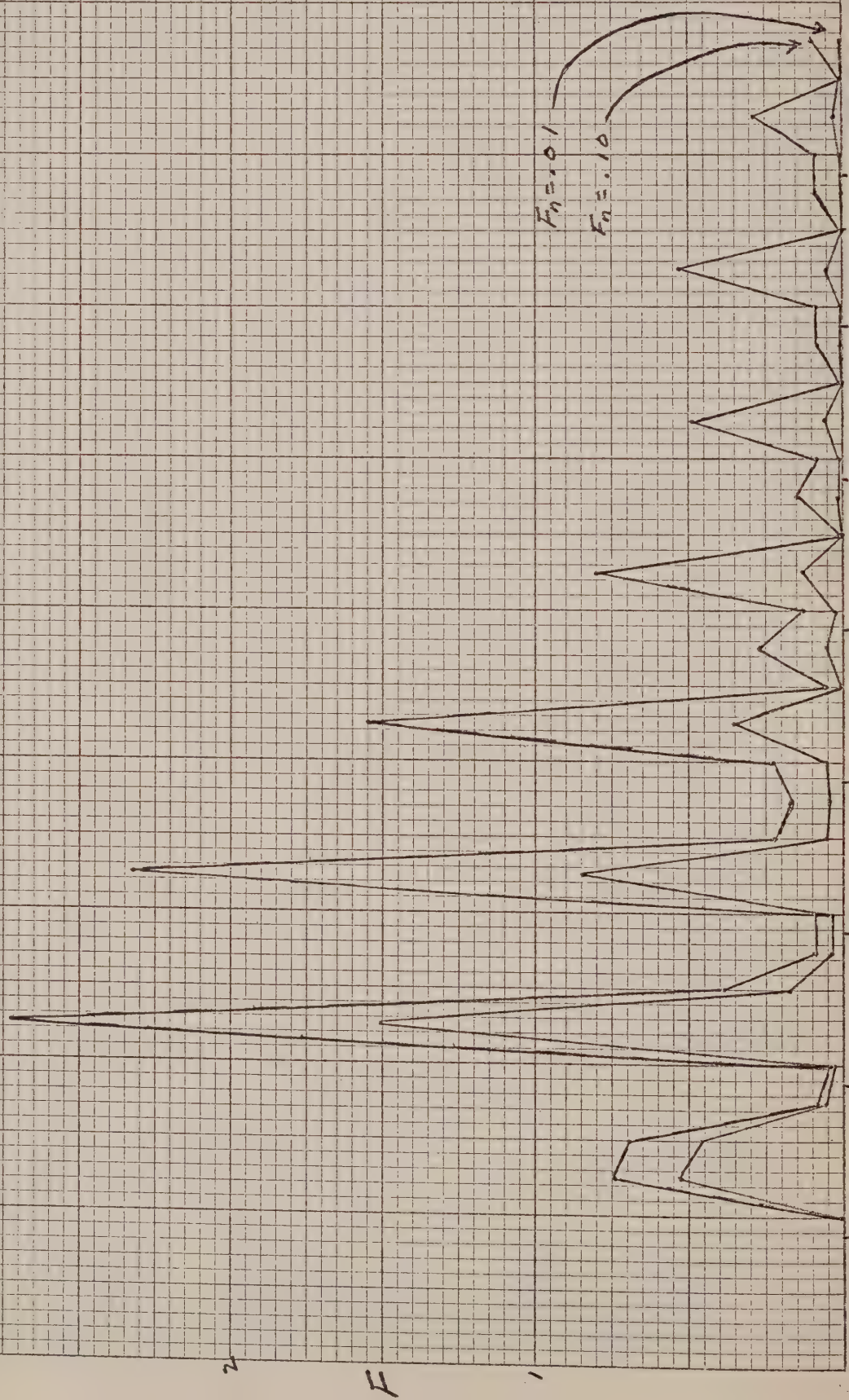


Figure 5 b. Cohort analysis estimates of F_i , annually,
for $DZ - VCZO$.

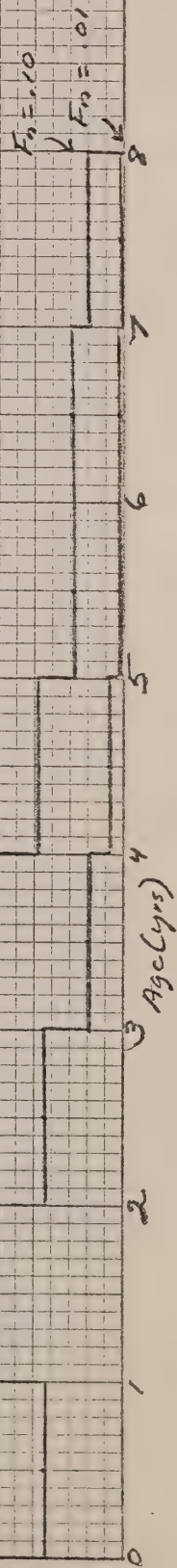


Figure 6. Actual data and fitted regression model,
PI-YC10, quarterly.

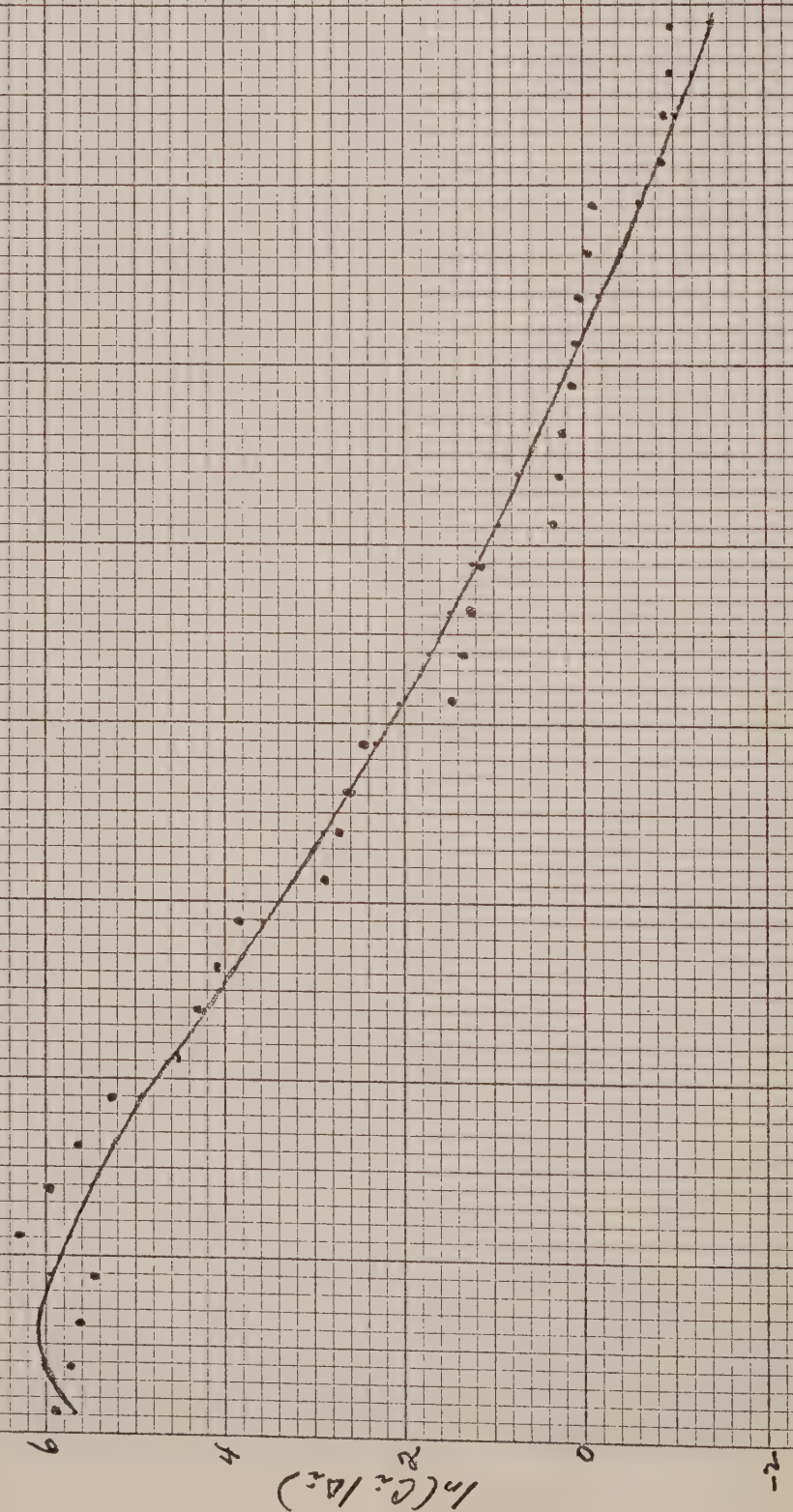


Figure 7. Actual data and fitted regression model,
 DI-YC10, annually.

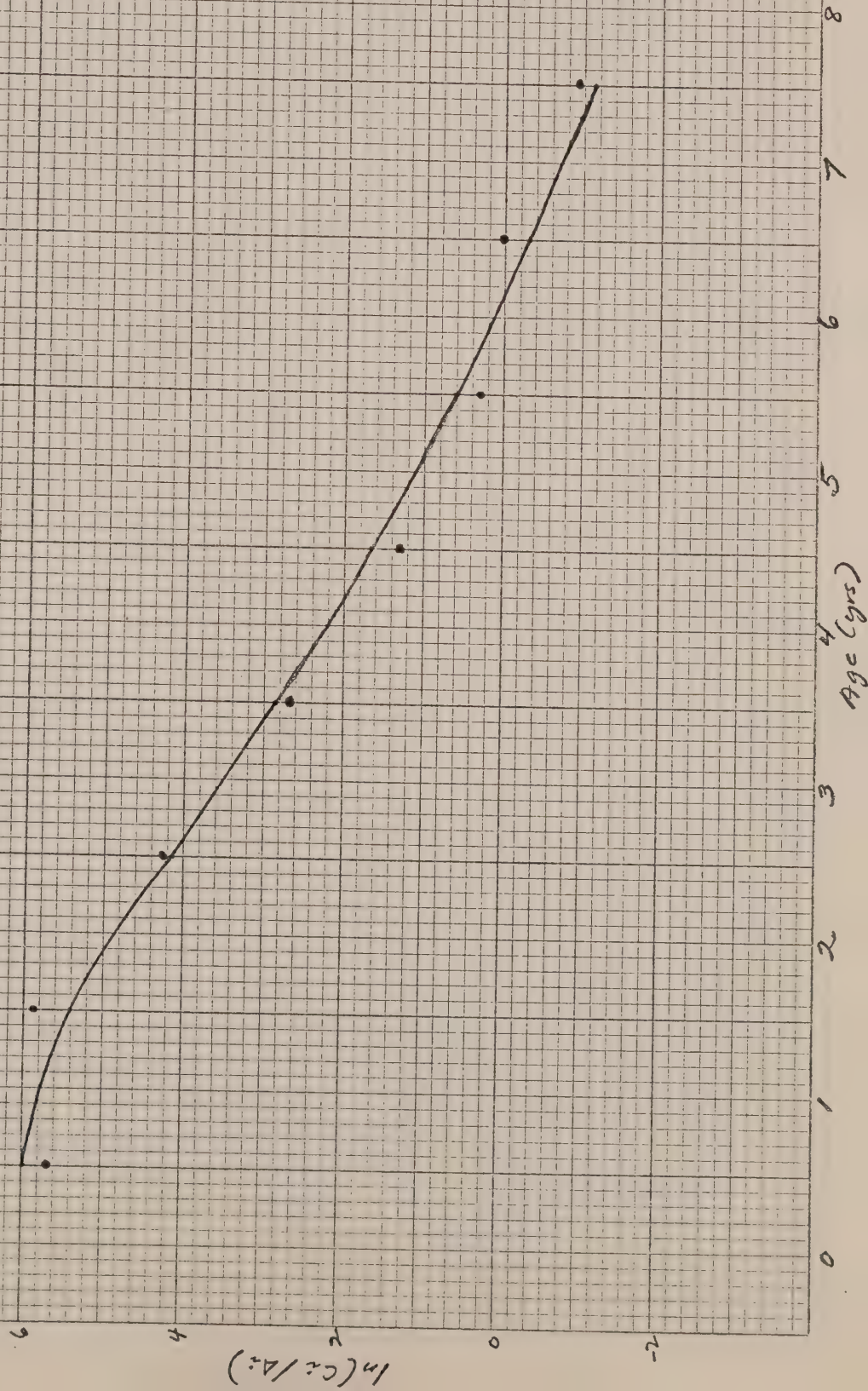


Figure 8. Actual data and fitted regression model,
DZ - YG20, quarterly.

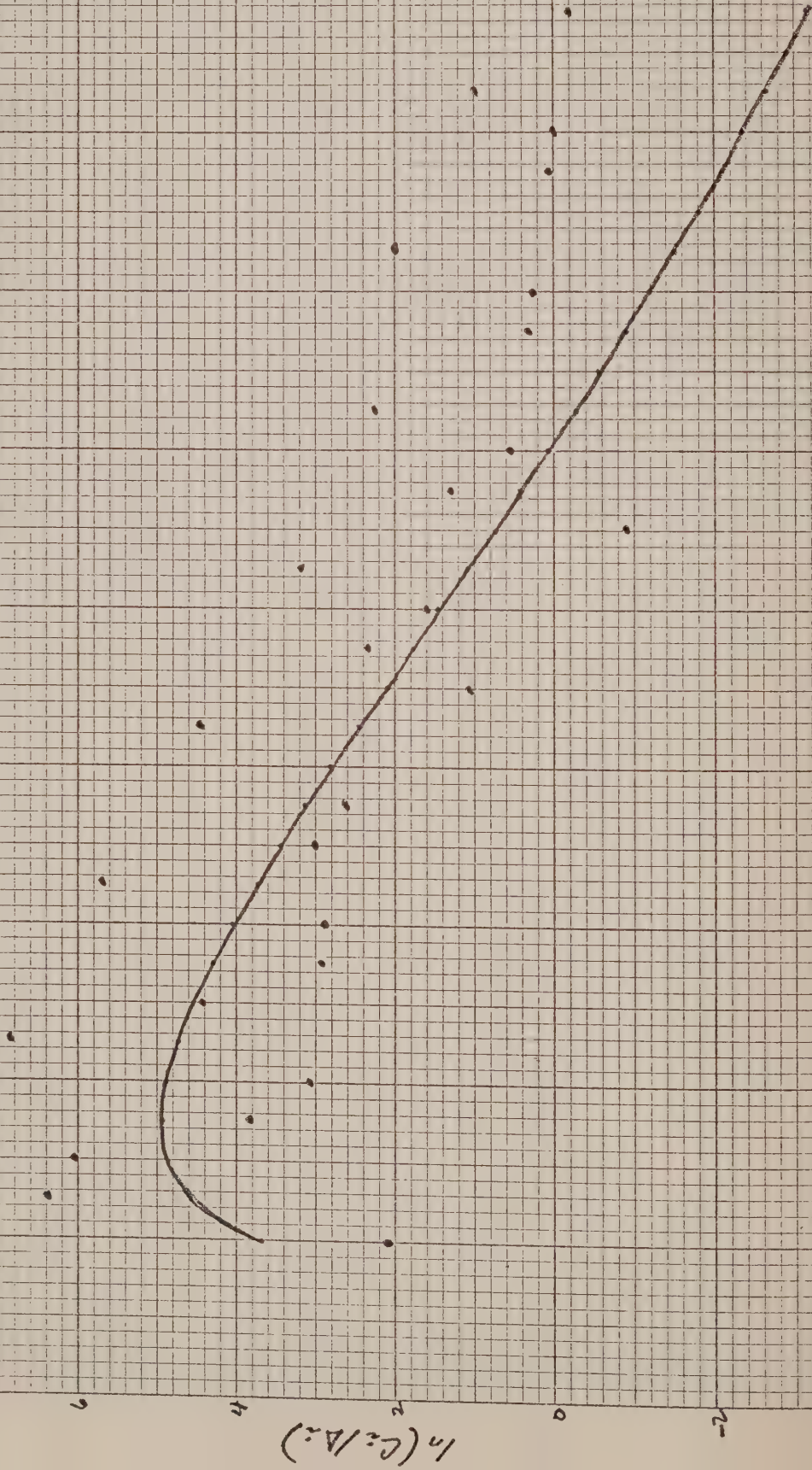


Figure 9. Actual data and fitted regression model,
 $DZ = YC20$, annually.

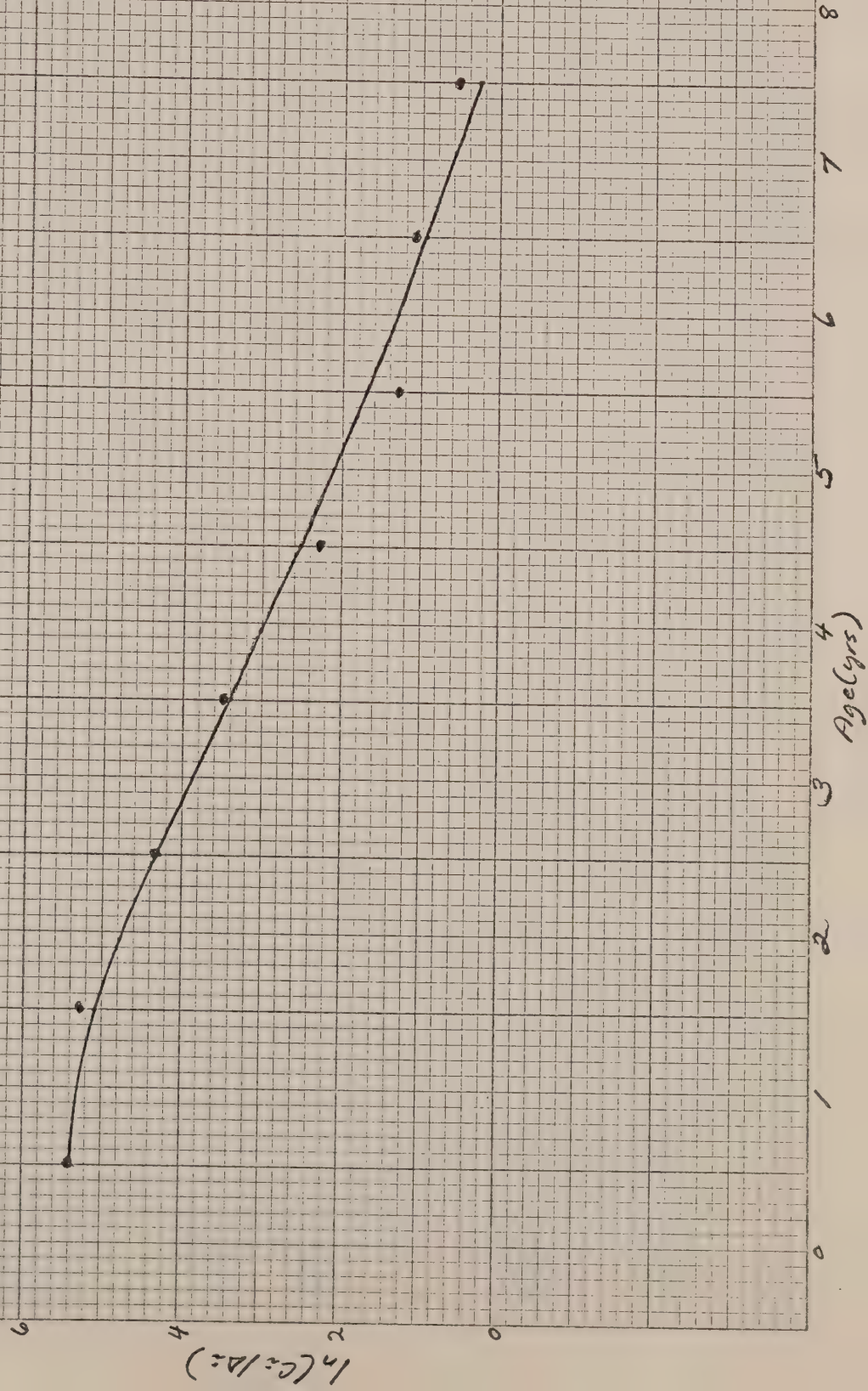


Figure 10. Regression estimates of F at interval midpoints (x) and actual average F during intervals ($-$), for DI-YC10.

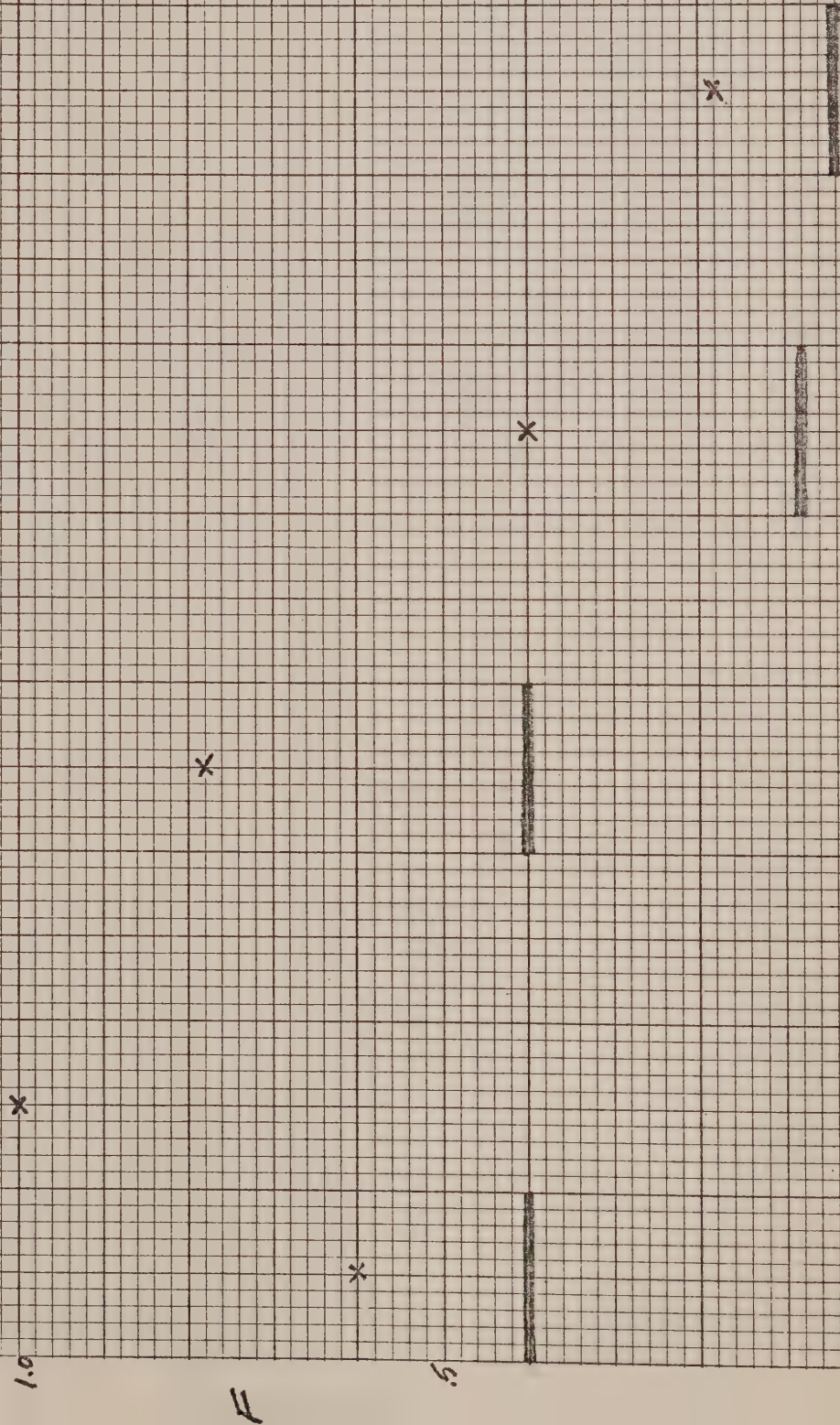


Figure 11. Regression estimates of F at interval midpoints (x) and actual average F during intervals ($\bar{F}$), for $DZ - YC 20$.

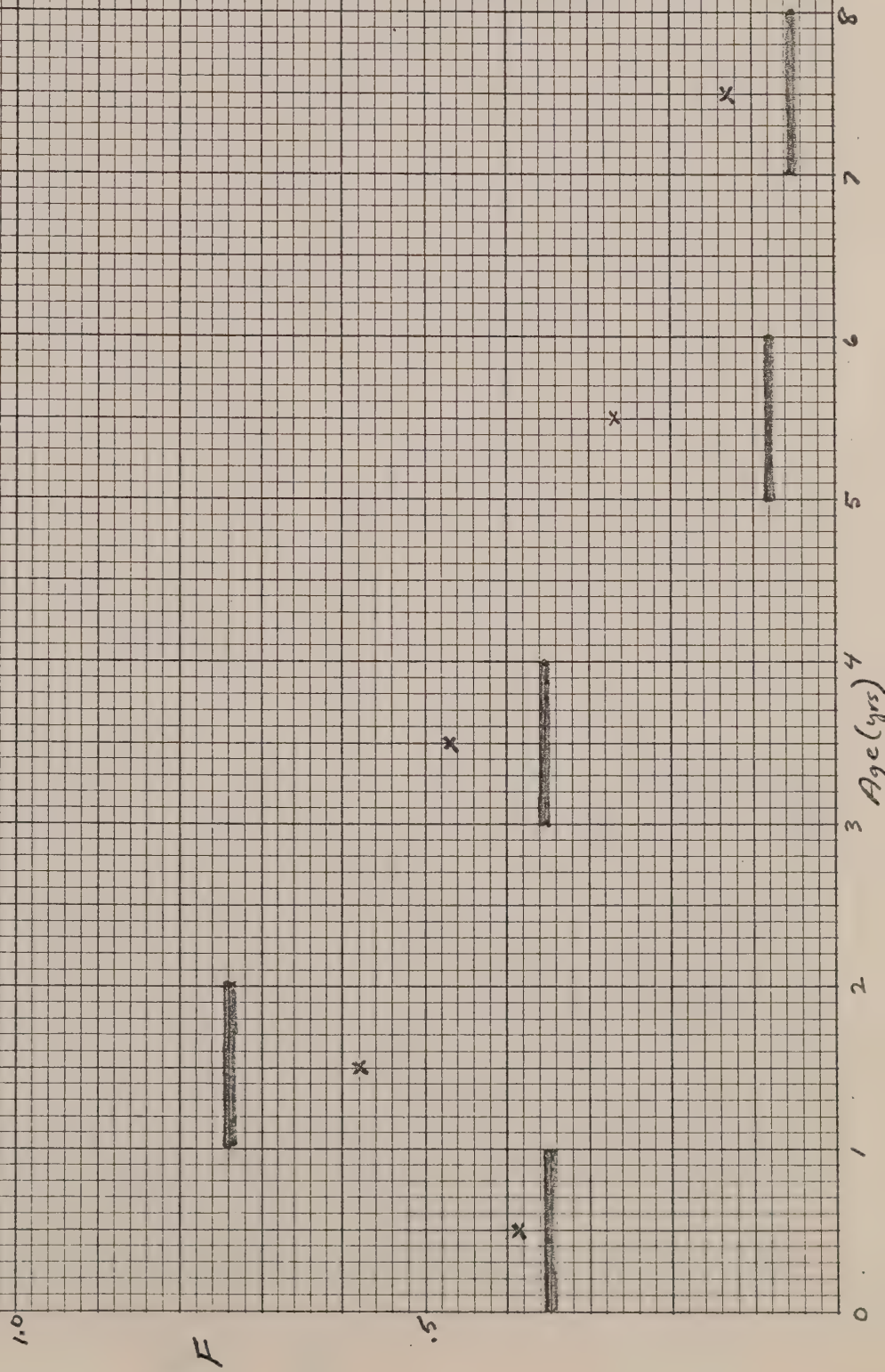


Figure 12a. Cohort analysis estimator of F_i , quarterly,
Albacore year-class 1961.

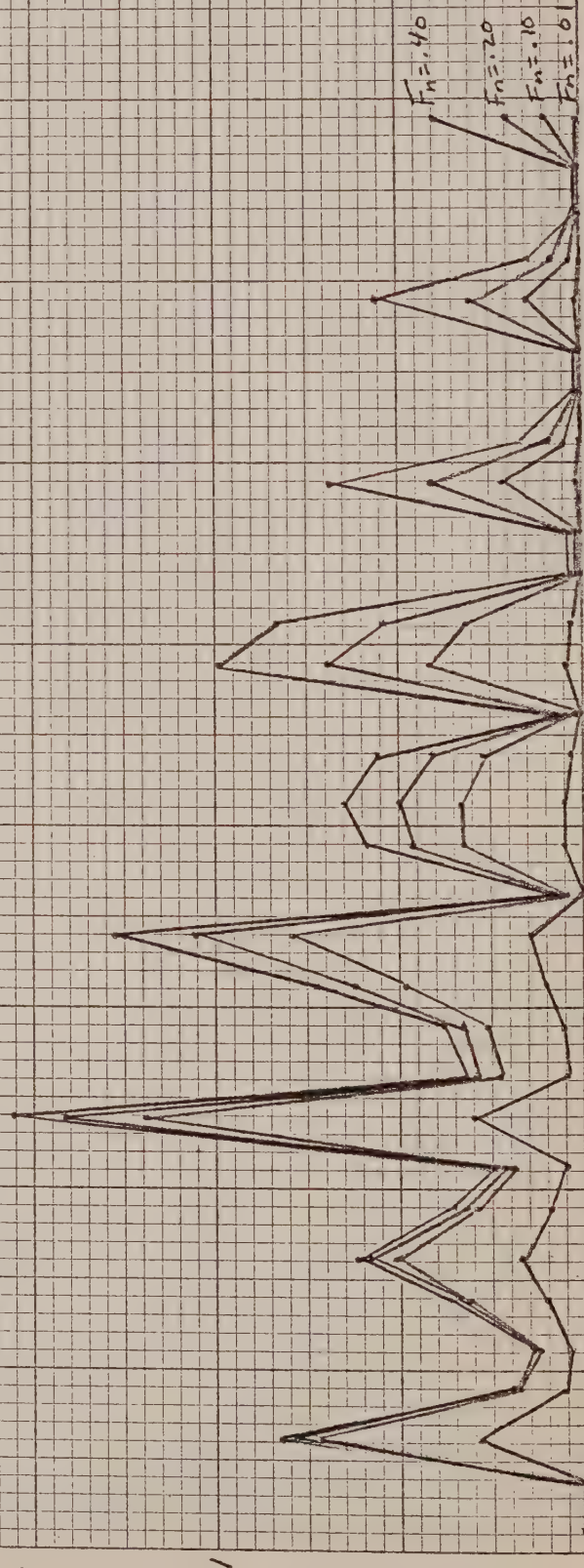


Figure 12-b Cohort analysis estimates of F_t , annually,
for elbaware year-class 1961.

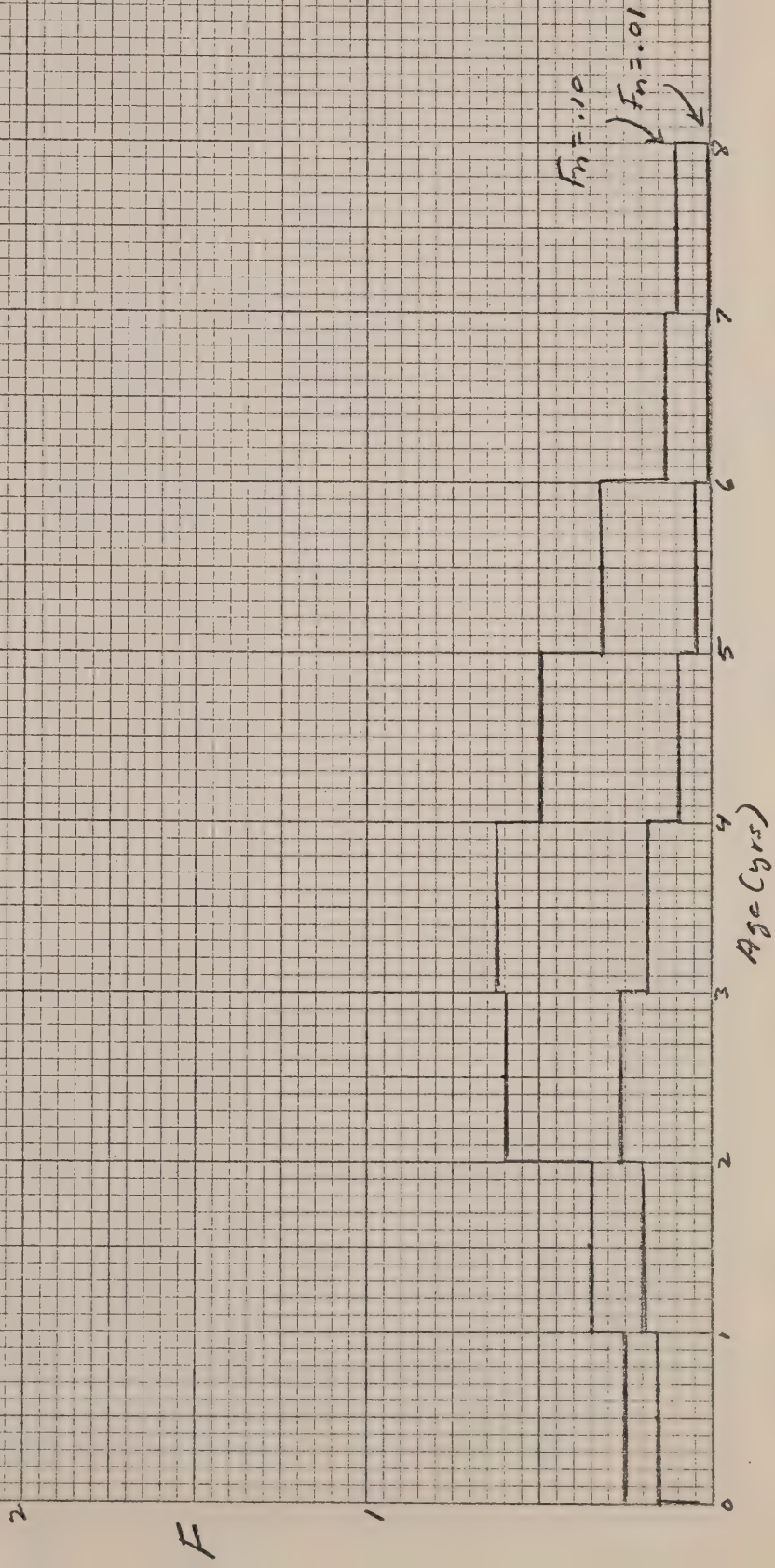


Figure 13a. Cohort analysis estimates of F_t , quarterly,
for albacore year-classes 1957-61.

2

F

1

$$F_n = .01$$

$$F_n = .10$$

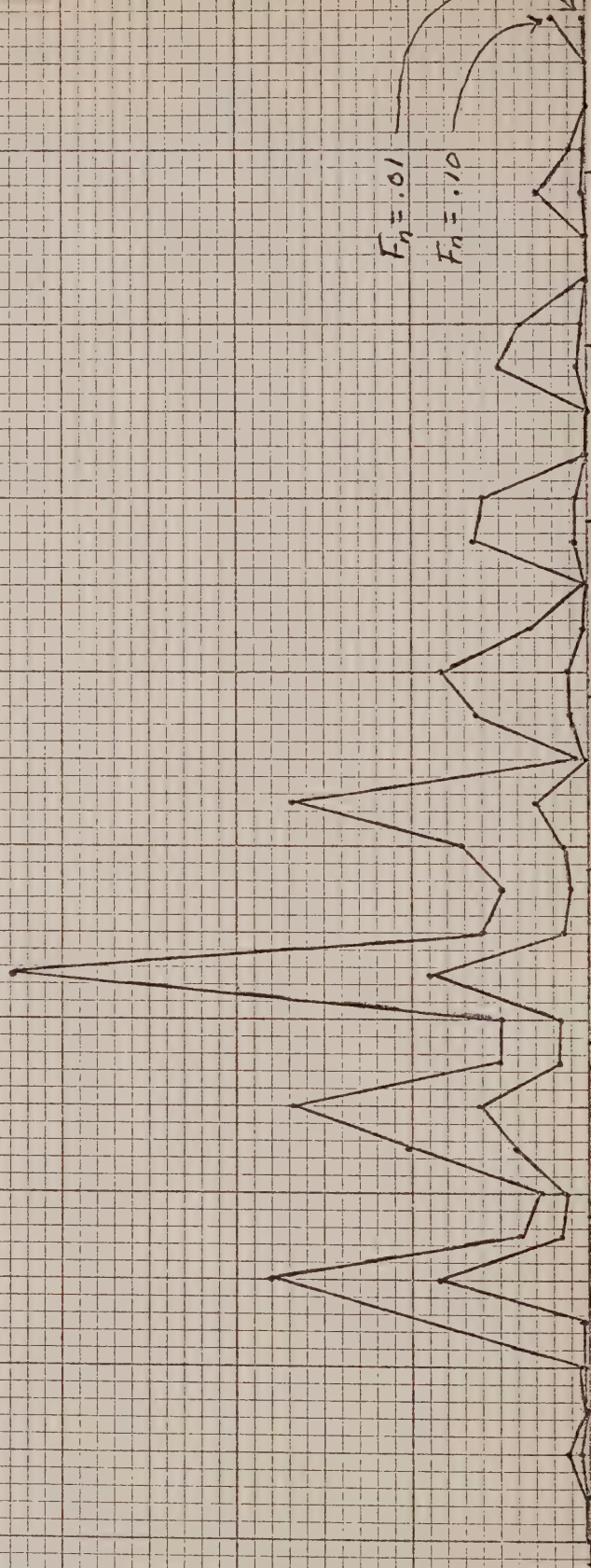


Figure 13b. Cohort analysis estimates of F_t , annually, for combined Albacore year-classes 1957-61.

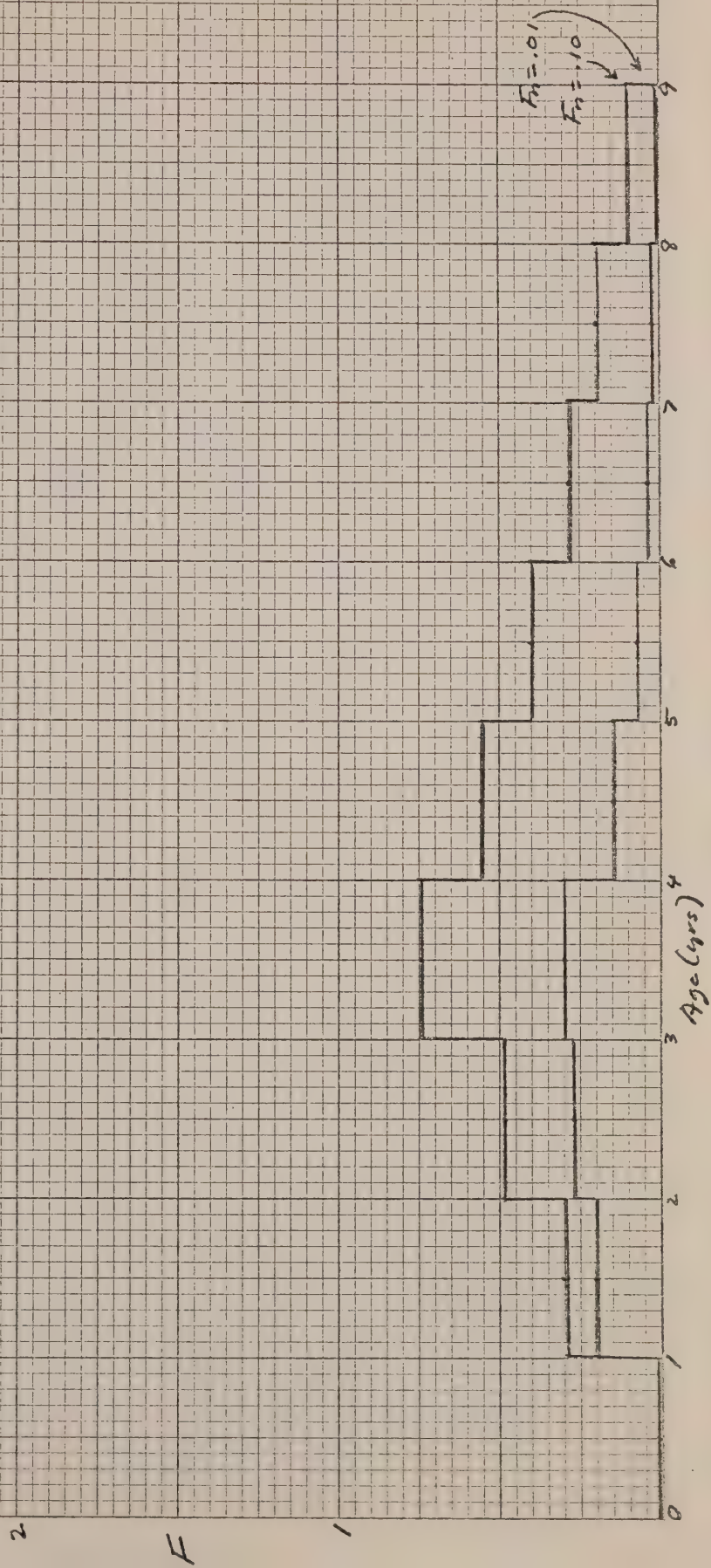


Figure 14. Actual data and fitted regression model, albacore year-class 1961, quarterly.

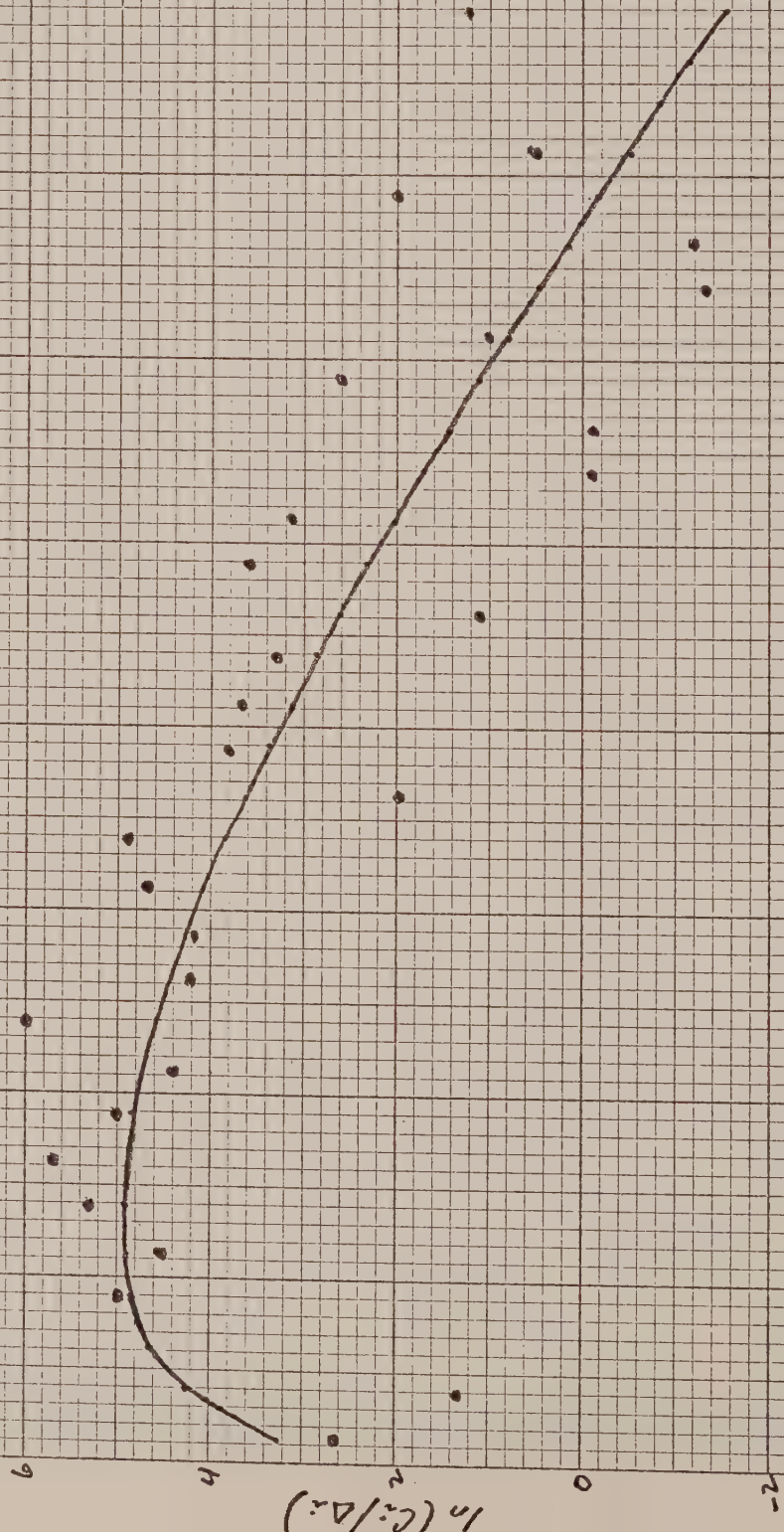


Figure 15. Actual data and fitted regression model, albacore year-class 1961, annually.

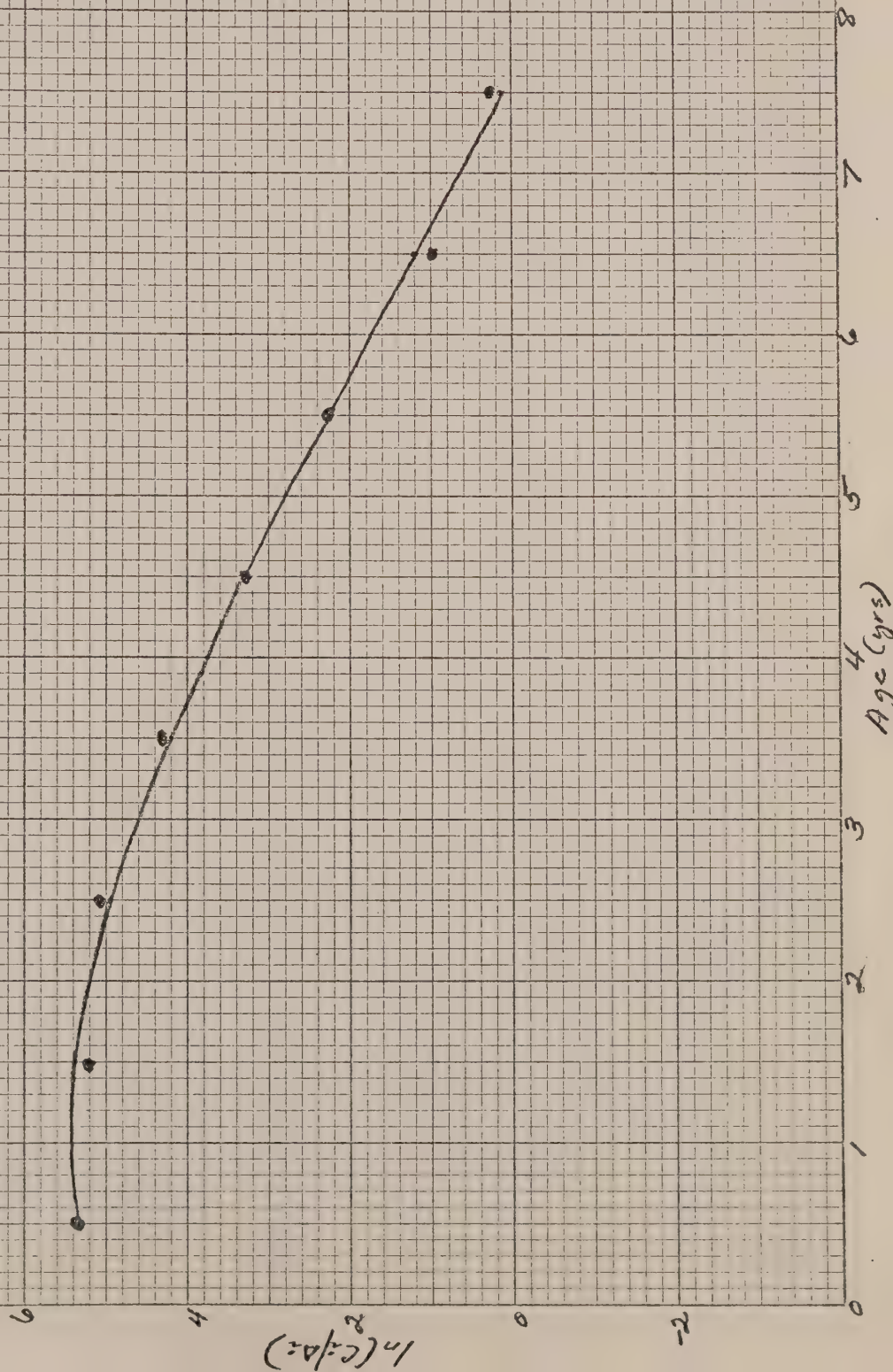


Figure 16. Actual data and fitted regression model,
 albatross year-classes 1957-61, quarterly

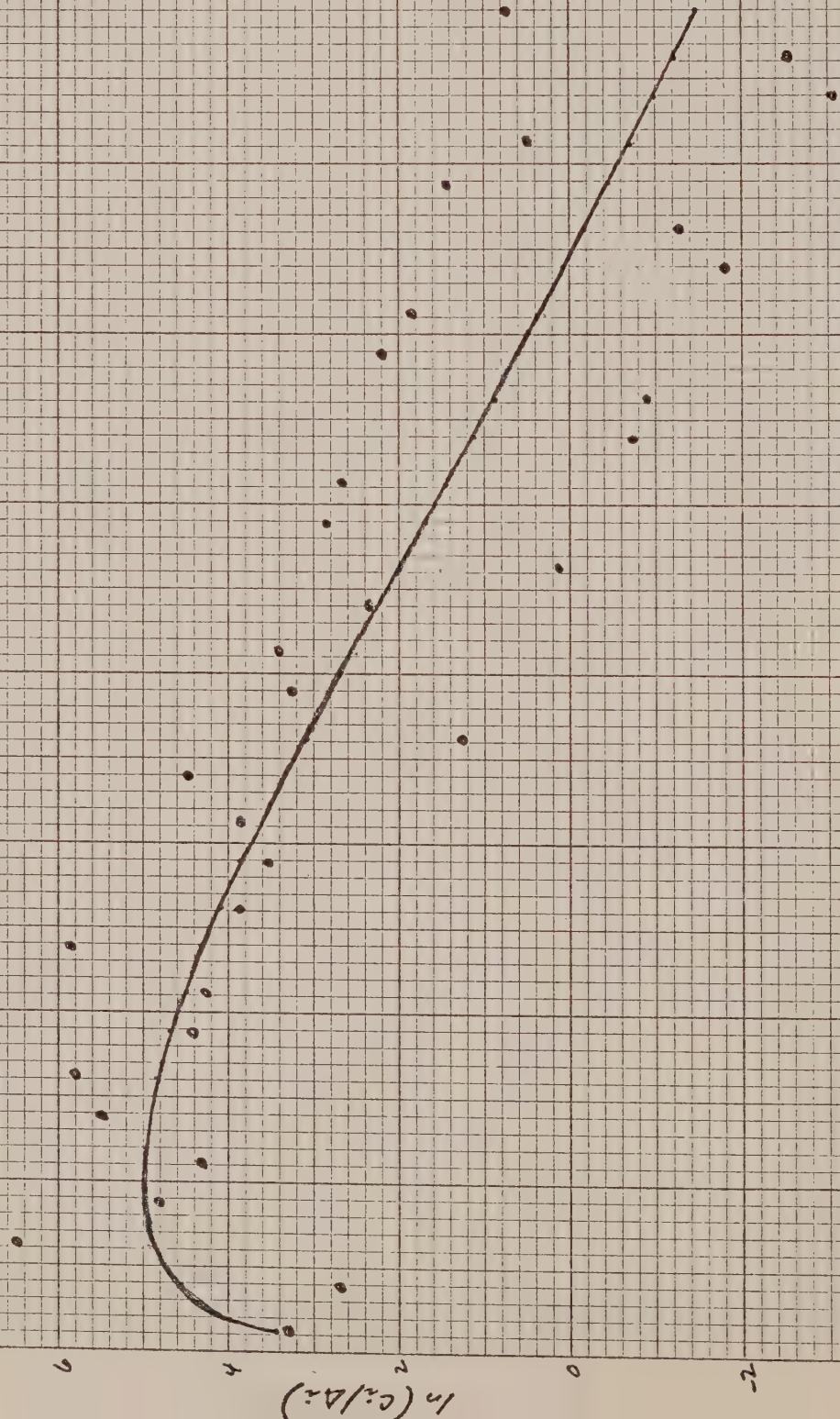
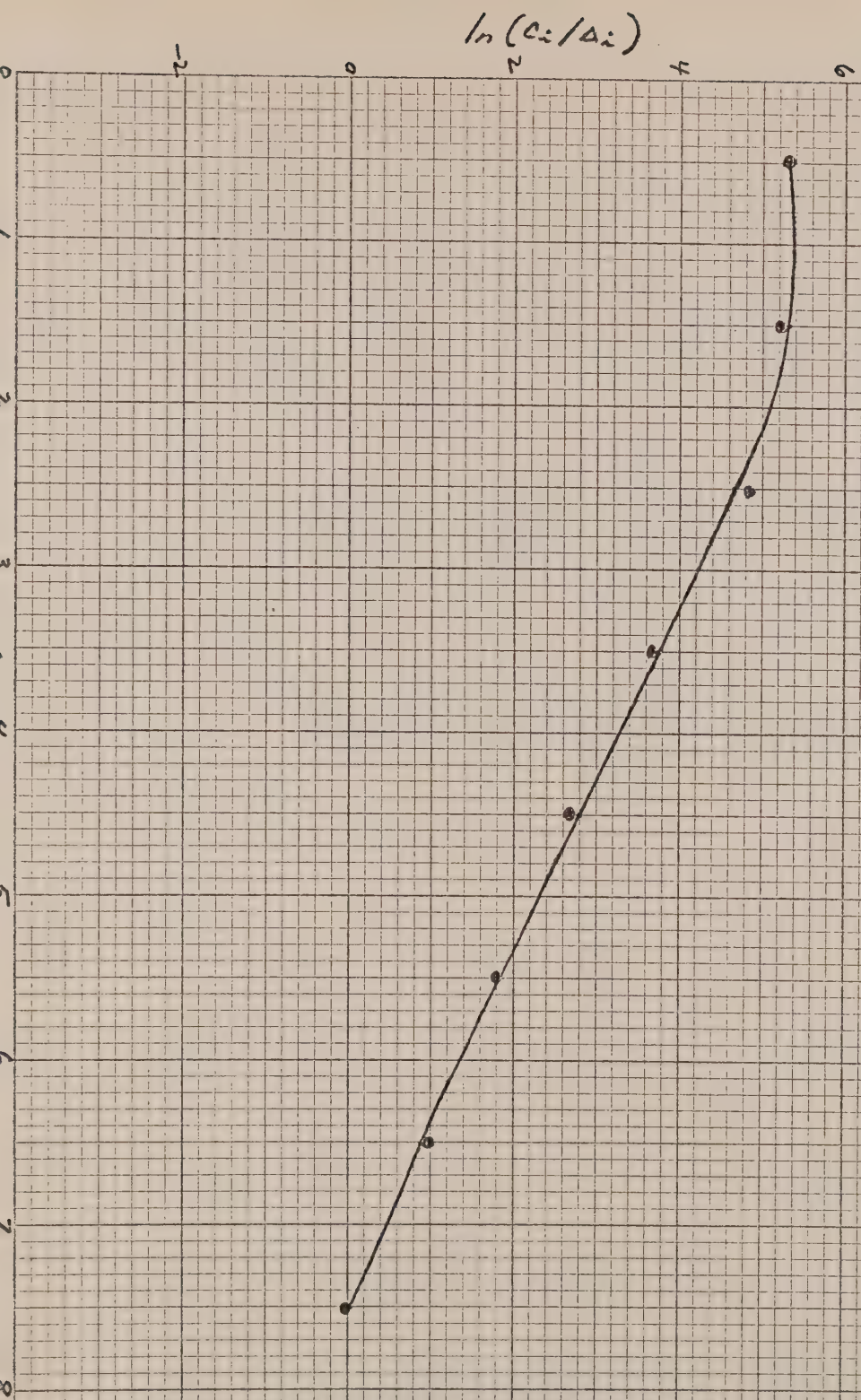


Figure 17. Actual data and fitted regression model, Alabama year-classes 1957-61, annual.



ESTIMATES OF GROWTH RATES FOR NORTH PACIFIC ALBACORE,
THUNNUS ALALUNGA (BONNATERRE), BASED ON AN ANALYSIS OF TAG RETURNS¹

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INTRODUCTION

Growth rates of North Pacific albacore, Thunnus alalunga (Bonnaterre), have been estimated by counting vertebral rings (Uno 1936; Aikawa and Kato 1938; Partlo 1955), examining scale circuli (Nose et al. 1957; Bell 1962; Yabuta and Yukinawa 1963), tracing progressions of length modes (Brock 1943; Suda 1954), and by measuring tagged fish at release and recapture (Otsu 1960; Clemens 1961). Of these techniques, only tagging provides direct estimates of growth rate, and the tagging results of Otsu and Clemens are reasonably consistent with the conclusions of Yabuta and Yukinawa's scale analysis and Suda's modal progression work. However, as Shomura (1966) noted in a review of tuna growth studies, comparisons are complicated by the biases and uncertainties peculiar to each method. For example, in the case of tagging we assume that the growth rate is unaffected by stresses resulting from capture, handling and tagging, and from the burden of carrying the tag itself. Conclusive results will require that the basic assumptions of any particular method be tested and verified.

In this paper, we present new estimates of growth parameters based on recent tag-recapture experiments conducted jointly by the National Marine Fisheries Service (NMFS) and the American Fishermen's Research Foundation (AFRF).³ We use the standard von Bertalanffy growth model, but also briefly explore some extensions. Sequential estimation of the parameters L_{∞} and K allows us to test hypotheses concerning variation in growth rate between tagged fish recaptured in different ocean regions.

³AFRF administers revenues derived from a landing assessment paid by U.S. albacore fishers.

Transpacific recaptures of albacore tagged in the eastern North Pacific off the U.S. west coast and in the western North Pacific off Japan have established the interdependence of the United States and Japanese North Pacific albacore fisheries, and have also fostered the hypothesis of a single, common stock (Ganssle and Clemens 1953; Clemens 1961; Otsu and Uchida 1963; Laurs and Lynn MS.⁴ However, our results add to growing

⁴Laurs, R. M., and R. J. Lynn. Manuscr. in prep. Seasonal migration of North Pacific albacore, Thunnus alalunga, into North American coastal waters: Distribution, relative abundance, and association with Transition zone waters. Southwest Fisheries Center, La Jolla Laboratory, National Marine Fisheries Service, NOAA, La Jolla, CA 92038.

evidence that the North Pacific albacore population is not homogeneous, as usually assumed, but is composed of at least two subgroups with different migration patterns, energy budgets, and growth histories.

METHODS

Tagging Procedures

Albacore were caught in the eastern North Pacific and tagged aboard U.S. commercial jig and bait fishing vessels on charter to AFRF. Approximately 70% of the tagging was done by commercial fishermen trained in tagging procedures, the rest by NMFS technicians. Single Floy⁵

⁵Mention of a commercial company or product does not constitute an endorsement by the National Marine Fisheries Service, NOAA.

spaghetti-dart tags were inserted on the left side below the second dorsal fin with the aid of a beveled stainless steel tube, so that the tag barb was lodged in the pterygiophores of the fin. Only fish judged to be in very good condition were tagged; fish hooked in the roof of the mouth or showing signs of extreme exhaustion or severe bleeding were rejected.

For each tagged fish a record was kept on (1) tag number, (2) date and time of release, (3) fork length at time of release, (4) condition at tagging, and (5) longitude and latitude of release. Additional tagging details are given in Laurs et al. (1976).

Recovery Procedures

Recoveries were made by sport and commercial fishers, unloaders, and cannery workers. In most cases information was obtained on (1) tag number, (2) date of recapture, (3) fork length at time of recovery, and (4) longitude and latitude of recapture. Most recapture locations were given as loran coordinates, which we converted to longitude and latitude, but the recapture locations for tags recovered by unloaders and cannery workers were often reported inexactly, e.g., as "off central California." Direct measurements of fork length were available for about half the fish recovered. For most of the remainder only the weight at recovery was given, and fork length was estimated using Clemens' (1961) weight-length relation.

Data Screening

The tag return data were screened to exclude cases where information was incomplete, unreliable, or clearly inaccurate. Out of 443 tag returns made from 1971 through 1976, 201 were rejected (Table 1). In 6 cases length at release was not measured, in 88 cases the recapture date was unknown, and in 50 cases neither length nor weight was measured at recovery. In 43 other rejected cases the length at recovery was not measured and the weight only guessed without the

use of scales. Additionally, in 13 instances a gross error was apparent in the measurement of fork length either at release or recovery.

The final accepted data set of 242 cases includes observations on 19 albacore showing negative estimated growth. We assume these are a result solely of measurement error, or error in estimation in cases where the recovery weight was converted to length, and we assume such error occurs throughout the data set independently of size or time out.

One of the common steps in screening tag recovery data for growth studies is to partition the data according to length at release, compute linear regressions of growth increment on time out within each subset, and then reject rare observations, say those departing from expectations by more than two standard deviations (Schaefer et al. 1961; Joseph and Calkins 1969). We abandoned this step because the 14 "outliers" it identified were actually statistically consistent with the three regression models, because the procedure has no sensible stopping rule, and because even with length at release fixed the expected relationship between growth increment and time out is nonlinear.

Grouping of Data

The selected data were cross-classified by location of tagging and location of recapture (Table 2). Forty-eight percent of the 242 tagged fish were released inshore (east of 130°W), and of these 67% were released south of 38°N, the remainder north of this latitude. Eighty-one percent of recaptured fish released south of 38°N were recovered in the same area, with 18% recovered either inshore north

of 38°N or west of the 180° line. Of the recovered fish tagged north of 38°N , only 18% were recaptured inshore south of 38°N , and the rest were recovered in the northern inshore area or in the eastern hemisphere. Of the recovered fish tagged and released offshore (west of 130°W), 75% were recaptured either inshore north of 38°N or west of 180° , and only 24% were recovered in the southern inshore area.

Tag returns were grouped into three categories depending on recapture location:

1. Group A includes all fish recaptured inshore south of 38°N , except those released inshore north of 38°N .
2. Group B consists of tag recoveries made inshore north of 38°N , excluding those released inshore south of 38°N .
3. Group C includes all tag recoveries made west of the 180° meridian.

The three groups together comprise 227 recaptues; excluded are seven fish tagged inshore north of 38°N and recovered south of this line, six fish released south of 38°N and recaptured in the northern inshore area, and the two tags with no information on recovery location.

Growth Models

We used observations on growth increment, length at tagging and time at liberty to estimate the growth rate, K , and the asymptotic length L_{∞} , of the standard deterministic von Bertalanffy model. In addition, we considered some extensions of the von Bertalanffy model which allow the growth rate to vary with age in a simple manner.

In general terms, we assumed that the expected growth increment for the j^{th} fish in the i^{th} group ($i = 1, \dots, m; j = 1, 2, \dots, n_i$), given the initial length and time out, could be stated as

$$E(\Delta L_{ij}) = \int_{t_{ij}}^{t_{ij} + \Delta_{ij}} G(u) (L_{\infty} - L(u)) du$$

where

$$\begin{aligned} E(\Delta L_{ij}) &= \text{expected growth increment of } j^{\text{th}} \text{ tagged fish in} \\ &\quad i^{\text{th}} \text{ group during } (t_{ij}, t_{ij} + \Delta_{ij}) \\ &= L(t_{ij} + \Delta_{ij}) - L(t_{ij}) \end{aligned}$$

t_{ij} = age of j^{th} fish in i^{th} group at time of release

Δ_{ij} = time at liberty for j^{th} fish in i^{th} group

$L(u)$ = length at age u

L_{∞} = asymptotic length

$G(u)$ = unspecified age-dependent growth rate.

If we set $G(u) = K = \text{constant}$, we have the standard von Bertalanffy model, and

$$E(\Delta L_{ij}) = (L_{\infty} - L_{1ij}) [1 - \exp(-K \Delta_{ij})]$$

where $L_{1ij} = L(t_{ij})$.

We call this Model 1. (In this model and others that follow, we omit subscripts on parameters, even though group-specific parameters are implied.)

In Model 1 we assume that the ratio of instantaneous growth rate $\frac{dL(u)}{du}$, to potential growth, $L_\infty - L(u)$, is K , a constant. Instead, we may suppose generally that this ratio varies with age. We considered two such situations. In the first, Model 2, we assume that stresses due to capture, handling, and tagging will initially reduce the growth rate of a tagged fish below its usual level, but that as time passes the normal growth process will be restored. Specifically, in our analysis of Model 2 we assume the standard model holds for untagged fish but that when a fish is tagged its normal growth pattern is interrupted, such that

$$\begin{aligned} G(u) &= K, & 0 < u < t_{ij} \\ G(u) &= K\{1 - \alpha \exp[-\beta(u - t_{ij})]\}, & t_{ij} \leq u \end{aligned}$$

We assume $K \geq 0$, $\beta > 0$ and $0 \leq \alpha \leq 1$.

Model 2 says that following tagging the growth rate is immediately reduced to a fraction $(1 - \alpha)$ of its normal value, K , and then returns to K asymptotically (Figures 1A, 1B). L_∞ is assumed to be unaffected.

In the second extended model, Model 3, we assume the growth rate is a periodic function of time, with the same pattern of growth repeated within each successive year. In addition, we assume fish are born on the same date each year, so that each fish also follows the same age-specific growth cycles. Specifically, we let

$$G(u) = \alpha_1 \sin[\beta_1(u - \delta)] + \alpha_2 \cos[\beta_2(u - \delta)]$$

where α_1 and α_2 are amplitudes of the component functions, β_1 and β_2 are the respective frequencies and δ is a time lag which fixes the origin of the growth rate curve.

Parameter Estimation

In the standard von Bertalanffy model there are two parameters to be estimated, K and L_∞ . The usual approach is to estimate them simultaneously, and we did so using the FORTRAN program BGC4 written by P. K. Tomlinson (Abramson 1971). This routine finds K and L_∞ as those parameter values which minimize

$$S = \sum_{j=1}^{n_i} \{L_{2_{ij}} - [L_\infty - (L_\infty - L_{1_{ij}}) \exp(-K\Delta_{ij})]\}^2$$

where $L_{2_{ij}} = L(t_{ij} + \Delta_{ij})$.

Since $E(L_{2_{ij}})$ is a nonlinear function of K , parameter estimates derived using this procedure are prone to serious bias unless observations on $L_{2_{ij}}$ are made over a wide range of $L_{1_{ij}}$ and Δ_{ij} . Presumably, it is also desirable that they be made uniformly in the plane of these two variables.

The parameters of Models 2 and 3 may also be estimated jointly using nonlinear least squares methods, but estimates of L_∞ and correlated parameters suffer the same drawbacks as estimates of the standard von Bertalanffy model parameters derived from BGC4.

An alternative approach in fitting all three models is to estimate L_∞ and the other parameters sequentially. Where the oldest members of the population have been intensively sampled, a reasonable estimate of L_∞ (at least a lower bound) is the length of the largest fish seen in the catches. With this value of L_∞ determined, the other parameters may be estimated by the least squares method using the general model

$$y_{ij} = -\ln \left(\frac{L_{\infty} - L_{2_{ij}}}{L_{\infty} - L_{1_{ij}}} \right) = \int_{t_{ij}}^{t_{ij} + \Delta_{ij}} G(u) du + \epsilon_{ij}$$

where we assume the ϵ_{ij} are independent errors with zero means and variances σ^2 .

This approach handily accommodates any well-behaved form of $G(u)$. In the case of Model 1, the problem of estimating K reduces to a simple linear regression

$$y_{ij} = K \Delta_{ij} + \epsilon_{ij} \quad (1)$$

When reasonably accurate estimate of L_{∞} can be made by sampling the catches, this sequential estimation procedure for Model 1 has the advantage that the range of observations on $L_{1_{ij}}$ and Δ_{ij} is not so critical.

With Model 2, the sequential method may be applied to estimate K , α , and β using the equation

$$y_{ij} = K \Delta_{ij} - \left(\frac{K\alpha}{\beta} \right) [1 - \exp(-\beta \Delta_{ij})] + \epsilon_{ij} \quad (2)$$

The desirability of fitting this nonlinear model to any particular set of data may be judged by examining the residuals around the least squares fit of Model 1 (equation 1). As is evident from Figure 2, the detection of nonlinearity in this manner requires that observations be available uniformly over a broad range of Δ_{ij} .

Model 3 parameters α_1 , α_2 , β_1 , β_2 , and δ may be estimated sequentially using

$$y_{ij} = \left(\frac{\alpha_2}{\beta_2}\right) \{\sin[\beta_2(t_{2_{ij}} - \delta)] - \sin[\beta_2(t_{1_{ij}} - \delta)]\} - \left(\frac{\alpha_1}{\beta_1}\right) \{\cos[-\beta_2(t_{2_{ij}} - \delta)] - \cos[\beta_1(t_{1_{ij}} - \delta)]\} + \varepsilon_{ij} \quad (3)$$

where $t_{1_{ij}} = t_{ij}$ and $t_{2_{ij}} = t_{ij} + \Delta_{ij}$.

Effective use of this model requires that most of the observed values of Δ_{ij} be no larger than about one-quarter of either wavelength, i.e., no larger than $\frac{\pi}{2\beta_1}$ or $\frac{\pi}{2\beta_2}$.

Covariance Analysis

One of our chief objectives was to determine whether growth rates differed between groups of fish, based on estimates of parameters of the standard von Bertalanffy model. Since BGC4 estimates of K and L_∞ are highly correlated, particularly when few large fish are in the sample, and since probability statements concerning intergroup comparisons of both K and L_∞ were not possible, we used the sequential estimation procedure. For the i^{th} group of fish we assumed

$$E(y_{ij}) = K_i \Delta_{ij} \quad (4)$$

where $y_{ij} = -\ln \left(\frac{L_\infty - L_{2_{ij}}}{L_\infty - L_{1_{ij}}} \right)$.

We set $L_{\infty} = 125$ cm for each group. Then we developed and applied a zero-intercept covariance analysis to test hypotheses of the form

$$H: K_1 = K_2 = \dots = K_m = K$$

on the basis of F statistics.

RESULTS

Standard Model

Table 3 Joint BGC4 estimates of K and L_{∞} for Groups A, B, and C are shown in Table 3. We consider the estimates inaccurate, owing to sampling biases discussed earlier. In particular, we think the unexpectedly low L_{∞} estimates (and correspondingly high K estimates) are due to the absence of very large albacore in the release and recovery samples. Of the 227 selected tag returns, 75 exceeded 80 cm in fork length at recapture, but only 18 were greater than 85 cm and just 3 were over 90 cm. The average fork length of tagged albacore at time of release was 63.5 cm (range from 48 to 89 cm), and at recovery, 75.7 cm (range from 51 to 96 cm).

Because of the difficulties with BGC4 estimates, we based intergroup comparisons on estimates of K from the sequential estimation procedure. A preliminary F-test showed no significant difference in $\hat{K}$ between those fish whose lengths at recovery were measured and those whose lengths were estimated from the weight-length relationship. Further sequential analyses (as well as the earlier BGC4 estimates) were therefore based on all data, regardless of how recovery length was determined.

L_{∞} was fixed at 125 cm. (This value is reasonable. Otsu and Sumida (1970) reported an albacore measuring 132.7 cm from the Hawaiian longline fishery, which harvests the very largest albacore known, but specimens over 125 cm are extremely rare.) Group A had the highest growth rate estimate, $\hat{K}_A = 0.210$ (Table 3). Group B had $\hat{K}_B = 0.191$, and Group C had the lowest growth rate estimate, $\hat{K}_C = 0.178$. When Groups B and C were pooled into a "North" category, the resulting $\hat{K}_N$ was 0.184. The estimate of K for all three groups combined was 0.192.

Table 3 also shows the statistics on average time between release and recapture. Group A fish were at liberty an average of 1.0 yr, while Group B fish were out 1.1 yr, and Group C fish, 1.5 yr. Tagged fish from Groups B and C combined were at large an average of 1.3 yr.

The estimates suggest that the "North" fish, Groups B and C, had a lower growth rate than the "South" fish of Group A. Such a difference might arise if, as we suppose, the "North" fish budget more of their available energy for migration compared with the "South" fish, and less for growth. The hypothesis of equal growth rates was tested using the zero-intercept analysis of covariance, and was rejected at the 5% significance level (Table 4, Figure 3). In pairwise comparisons between individual groups, the only significant difference in growth rate was between Groups A and C (Figure 4).

Are the observed differences in growth rates of tagged albacore consistent with other information? To check this, we examined the length

Fig. 5 composition of albacore catches along the U.S. west coast (Figure 5).

The length-frequency plot for catches north of 38°N during the period when most recaptures were made, 1972-75, showed modes at about 64 and 76 cm, and a hint of one at 54 cm. Catches south of 38°N showed the 54-cm mode, but had primary modes at about 67 and at 80 cm. The discrepancy between modes of the older albacore is further evidence of a slower growth rate for "North" fish, assuming these modes represent fish of the same age. To see if the length-frequency data and tag data agreed, we compared the ratio of $\hat{K}_B$ to $\hat{K}_A$, computed from the tag data, with the expected ratio of these parameters as a function of the difference in length at age, derived from the von Bertalanffy model, viz

$$\left(\frac{K_B}{K_A}\right)_{LF} = \frac{\ln\left(1 - \frac{L_B}{L_\infty}\right)}{\ln\left(1 - \frac{L_A}{L_\infty}\right)}$$

where L_B = length mode of older "North" inshore fish

L_A = length mode of older "South" inshore fish

Putting $L_\infty = 125$ cm and substituting $L_B = 76$ cm and $L_A = 80$ cm, we calculate that

$$\left(\frac{\hat{K}_B}{\hat{K}_A}\right)_{LF} \approx 0.92$$

and with $L_B = 64$ cm, $L_A = 67$ cm, and $L_\infty = 125$ cm, we have

$$\left(\frac{\hat{K}_B}{\hat{K}_A} \right)_{LF} = 0.93.$$

Now, taking the ratio of growth rate estimates derived from tag data we have

$$\left(\frac{\hat{K}_B}{\hat{K}_A} \right)_T = 0.91.$$

These results are strikingly similar and lend credibility to the covariance analysis.

An alternative way to judge the covariance results is to compute the expected fork length under each $\hat{K}$ at annual time steps and compare these with the observed modes of the length-frequency distributions. Starting with some initial fork length, L_1 , we used the equation $L_i = a + b L_{i-1}$, $i = 2, 3, \dots$, where $a = L_\infty (1 - \text{EXP}(-K))$ and $b = \text{EXP}(-K)$. Setting $L_1 = 54$ cm and $L_\infty = 125$ cm, we found the sequence of lengths 54.0, 66.3, and 76.5 cm for the Group B albacore, and 54.0, 67.4, and 78.3 cm for Group A fish. These are reasonably consistent with the observed sequences of length modes.

Extended Models

Plots of residuals from the standard model against days out did not suggest any particular pattern of systematic deviation from linearity. However, we thought that some of the variability could be attributed to "lack of fit" (Draper and Smith 1966), and examined the

two extended von Bertalanffy models. We fit Model 2 using the sequential estimation procedure (Equation 2) with $L_{\infty} = 125$ cm. In all cases the least squares estimates of α were on a boundary (0 or 1) and estimates of β were very large. Estimates of K were usually less than 4% larger (in Group A, 12.6% larger) than the corresponding estimates of K from the standard linear model. No significant reduction in residual mean squared error was achieved. Any impact of tagging on growth, of the sort hypothesized in Model 2, is probably masked by the extremely high variability in the data.

We also briefly considered Model 3. We fixed $L_{\infty} = 125$ cm and fitted the integrated form at Equation 3 to each group of data. The residual mean squared error from the periodic growth model was not significantly less than for Model 1 in any case. This result was not entirely unexpected; since the average time out was greater than 1 yr in each group, detection of seasonal variation in growth rate was effectively ruled out. On the other hand, any strong cycles with a period of about 4 yr or more should have been revealed, if present. Apparently most of the variability in y_{ij} is due either to random measurement errors, or to fluctuations arising from a simple stochastic growth process with expectation given by Equation 4.

DISCUSSIONS AND CONCLUSIONS

Our confidence in the growth analysis results is strengthened by their consistency with other findings, but the assumptions of our analysis need to be tested. In particular, we assumed that our estimate of L_{∞} , 125 cm, was the same for all groups of North Pacific albacore. If the "South" fish, Group A, actually tend toward a larger asymptote in fork length than the "North" fish of Groups B and C then the difference between estimates of K might not be significant. The value of L_{∞} is not too important; the same conclusions were obtained when we set L_{∞} equal to 120, 130, and 135. But the assumption of equality of the L_{∞} estimates is important, and testing it will be extremely difficult.

We also assumed that the growth rate was unaltered by the presence of the tag or by the stress imposed in its application. In our analysis of Model 2 we explored the question of whether tagging might have affected growth rate in a specified way, and Model 2 did not fit our data any better than the standard von Bertalanffy model, Model 1. Any effect of the sort we hypothesized might easily have been masked by high variance in the data. Nevertheless, if the effect of tagging were simply to reduce the normal growth rate, K , suddenly and permanently to a lower level, K' , it would go undetected by our analysis. To determine the validity of the tag-effect assumption we need to compare the growth rates of tagged fish with those of untagged, "control" fish. One promising approach is to combine tagging with recently developed procedures of otolith analysis (Pannella 1971; Brothers et

al. 1976; Struhsaker and Uchiyama 1976; Uchiyama and Struhsaker MS⁶).

⁶Uchiyama, J. H., and P. Struhsaker. Manuscr. in prep. Age and growth of skipjack tuna, Katsuwonus pelamis, and yellowfin tuna, Thunnus albacares, as indicated by daily growth increments of sagittae. Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service, NOAA, Honolulu, HI 96812.

If the otoliths of tagged fish are marked with tetracycline or some other osteophylic agent at the time of release, the information on time of liberty for recaptured fish can be used to determine the rate of ring formation (Inter-American Tropical Tuna Commission 1976). The usual assumption of daily ring deposition may then be tested. Further, the calibrated otolith method may then be used as the principal means of absolute age and growth determination, and may also be used to test assumptions of the tag-recapture method and other procedures. Planning of such experiments for North Pacific albacore is now underway.

We found that the growth rate of North Pacific albacore recaptured either north of 38°N in the U.S. fishery or in the western North Pacific off Japan was significantly lower than for tagged albacore recaptured in the U.S. fishery south of 38°N during 1972-75. The differences in growth rate of tagged fish are remarkably consistent with differences in length-frequency distributions of albacore caught off the United States north of south of 38°N during the period when most recaptures were made. These findings add to a growing body of evidence (Brock 1943; Laurs et al. 1975⁷; Laurs and Lynn 1976⁸; Laurs and Lynn MS⁴) that North Pacific albacore are not as homogeneous as

⁷Laurs, R. M., R. J. Lynn, and R. N. Nishimoto. 1975. Report of joint National Marine Fisheries Service-American Fishermen's Research Foundation albacore studies conducted during 1975. SWFC Admin. Rep. LJ-75-84, 49 p. Southwest Fisheries Center La Jolla Laboratory, National Marine Fisheries Service, NOAA, La Jolla, CA 92038.

⁸Laurs, R. M., and R. J. Lynn. 1976. Report of joint National Marine Fisheries Service-American Fishermen's Research Foundation albacore studies conducted during 1976. SWFC Admin. Rep. LJ-76-36, 51 p. Southwest Fisheries Center La Jolla Laboratory, National Marine Fisheries Service, NOAA, La Jolla, CA 92038.

usually assumed, and that there may be at least two subgroups of albacore: one which supported the Japanese pole-and-line fishery and the U.S. fishery in waters north of about 38°N from 1972 to 1975, and another which did not contribute significantly to the Japanese surface fishery, but supported the U.S. coastal fishery south of 38°N during this period. If such a distinction is valid, the situation is surely more complex and dynamic than we have supposed, with each stock's contribution to each fishery varying from year to year. Presumably such variation would be tied directly to changes in oceanographic conditions. And undoubtedly the latitudinal boundary was not fixed exactly at 38°N during 1971-76, as we assumed. If an accurate assignment of tagged fish to "stock" were possible a more powerful test of growth differences could be made.

A finding that more than one subpopulation or stock is involved in the North Pacific albacore fisheries would have very important consequences, of course, both for stock assessment, fishery evaluation and management policy analysis, and for development of accurate catch forecasting systems. It is important that further work be done to identify stocks, and to elucidate their origins, migratory habits, and degree of interchange.

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Table 1.--Number of tagged North Pacific albacore released, returned, rejected, and accepted for growth analysis.

Year	No. tagged fish released	No. tagged fish returned	Rejected tag returns					Total tag returns rejected	No. tag returns accepted for analysis
			Missing release size	Missing recapture date	Missing recovery size	Weight at recovery estimated	Gross measurement error		
1971	887	33	1	7	5	2	0	¹ 16	17
1972	1,556	126	1	31	14	11	6	63	63
1973	1,806	107	1	26	8	8	1	44	63
1974	2,490	130	2	20	16	15	5	58	72
1975	1,351	41	0	4	6	7	1	18	23
1976	<u>1,526</u>	<u>6</u>	<u>1</u>	<u>0</u>	<u>1</u>	<u>0</u>	<u>0</u>	<u>2</u>	<u>4</u>
Total	9,616	443	6	88	50	43	13	201	242

¹One return rejected because tag number was unknown.

Table 2.--Classification of selected tag data
by locations of release and recapture.

Recapture	Release				Grand total
	East of 130°W		Total	West of 130°W	
	South of 38°N	North of 38°N			
Eastern Pacific	69	23	92	87	179
South of 38°N	63	7	70	30	100
North of 38°N	6	16	22	57	79
Western Pacific	8	15	23	38	61
Unknown	1	0	1	1	2
Grand total	78	38	116	126	242

Table 3.--Estimates of von Bertalanffy growth parameters for North Pacific albacore by recapture location and estimation method.

Recapture group	Sample size n	BGC4 estimates		Sequential estimates		Average time out $\bar{\Delta}$ (yr)
		$\hat{L}_{\infty}$ (cm)	$\hat{K}$ (yr ⁻¹)	Fixed L_{∞} (cm)	$\hat{K}$ (yr ⁻¹)	
A	93	94.5	0.505	125.0	0.210	1.02
B	73	107.5	0.272	125.0	0.191	1.11
C	61	98.5	0.345	125.0	0.178	1.50
B+C	134	102.1	0.310	125.0	0.184	1.29
A+B+C	227	100.9	0.342	125.0	0.192	1.18

Table 4.--Analysis of covariance comparing growth rate of group A with growth rate of group (B+C). Asterisk indicates growth rates are different at 5% significance level.

Source of variation	d.f.	Residual SS	MS	F
Individual lines				
A	92	1.0310		
B+C	133	1.3351		
Pooled	225	2.3661	0.0105	
Common line	226	2.4267		
Difference	1	0.0606	0.0606	5.76**

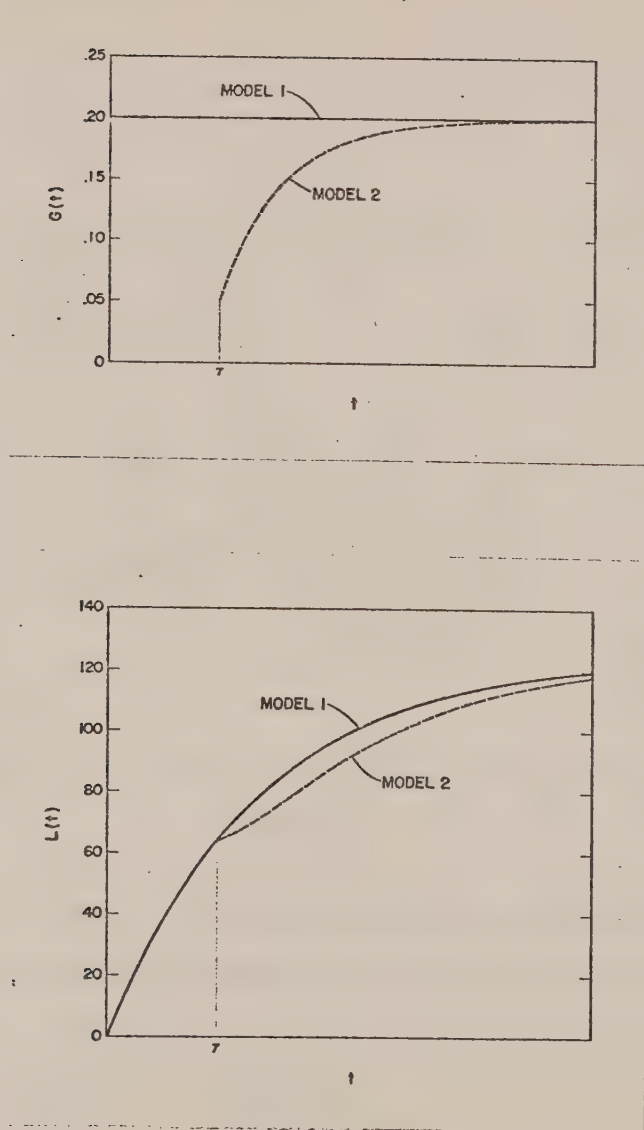


Figure 1.--Standard von Bertalanffy growth model (Model 1), and an extension (Model 2) incorporating a temporary reduction in growth rate, $G(t)$, following tagging at time τ . The resulting growth pattern, $L(t)$ is altered.

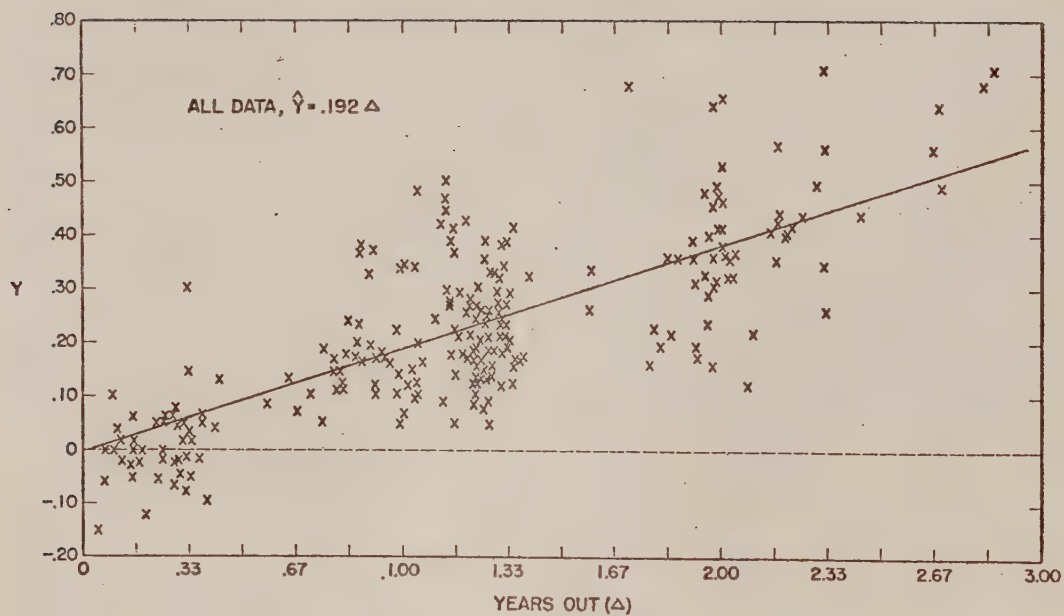


Figure 2.--Regression of growth variable, Y , on years between release and recapture for 227 North Pacific albacore of Groups A, B, and C combined.

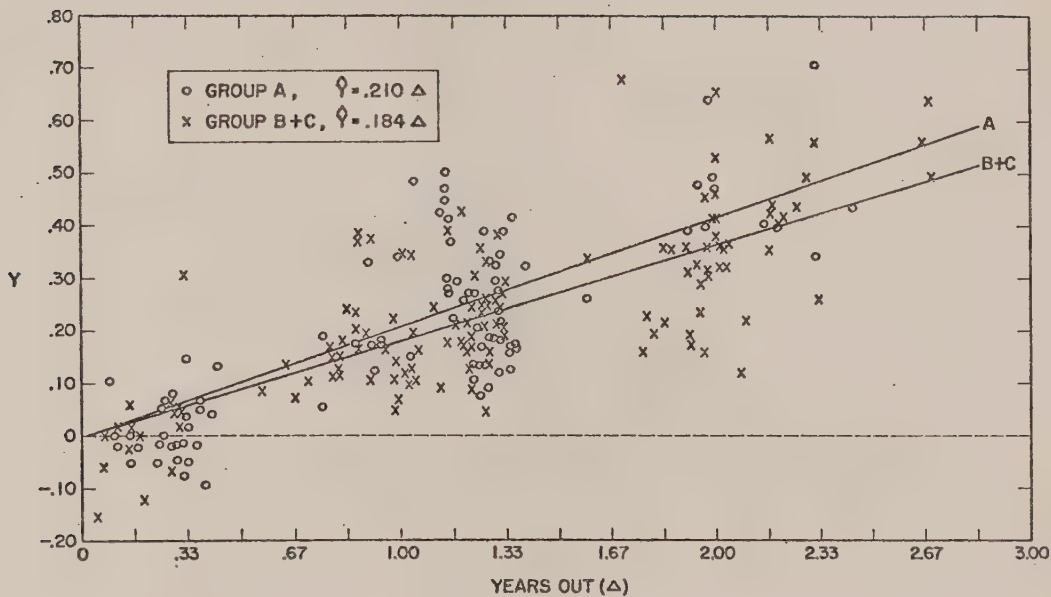


Figure 3.--Regression of growth variable, Y, on years between release and recapture for albacore of Groups A (93 fish) and B + C (134 fish). The slopes are estimates of the von Bertalanffy growth parameter, K, and they are significantly different.

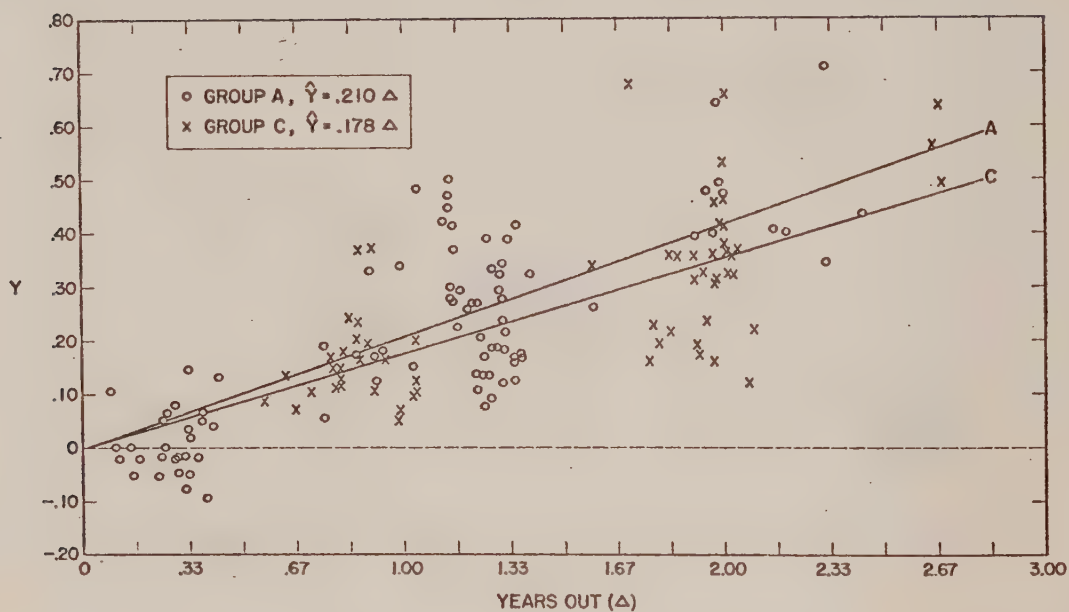


Figure 4.--Regression of growth variable, Y, on years between release and recapture for albacore of Groups A (93 fish) and C (61 fish). The slopes are estimates of the von Bertalanffy growth parameter, K, and they are significantly different.

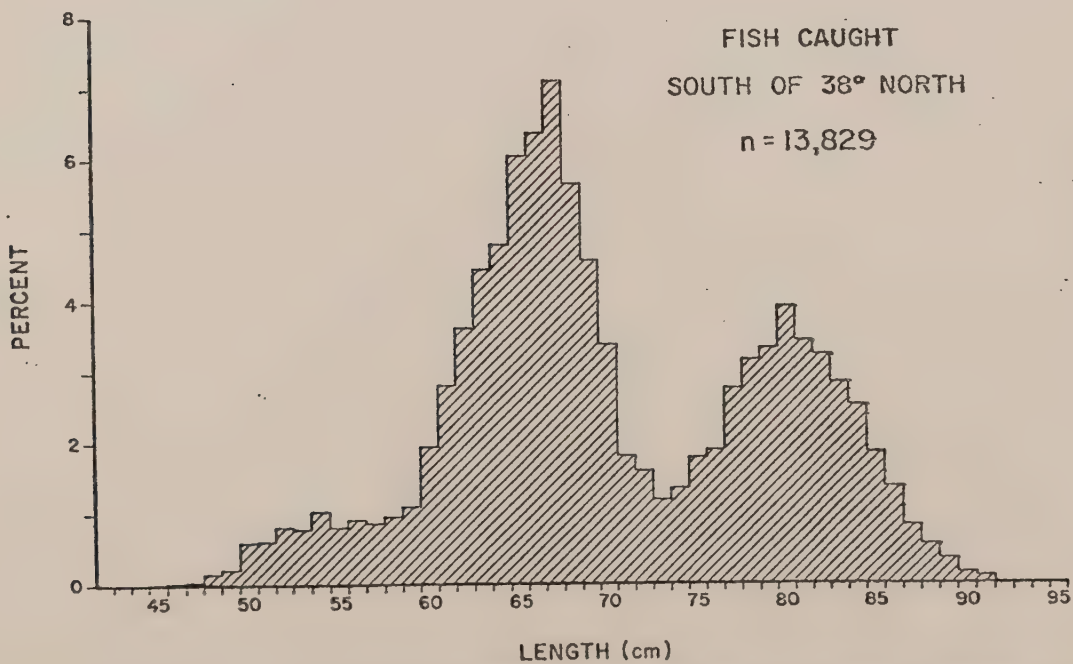
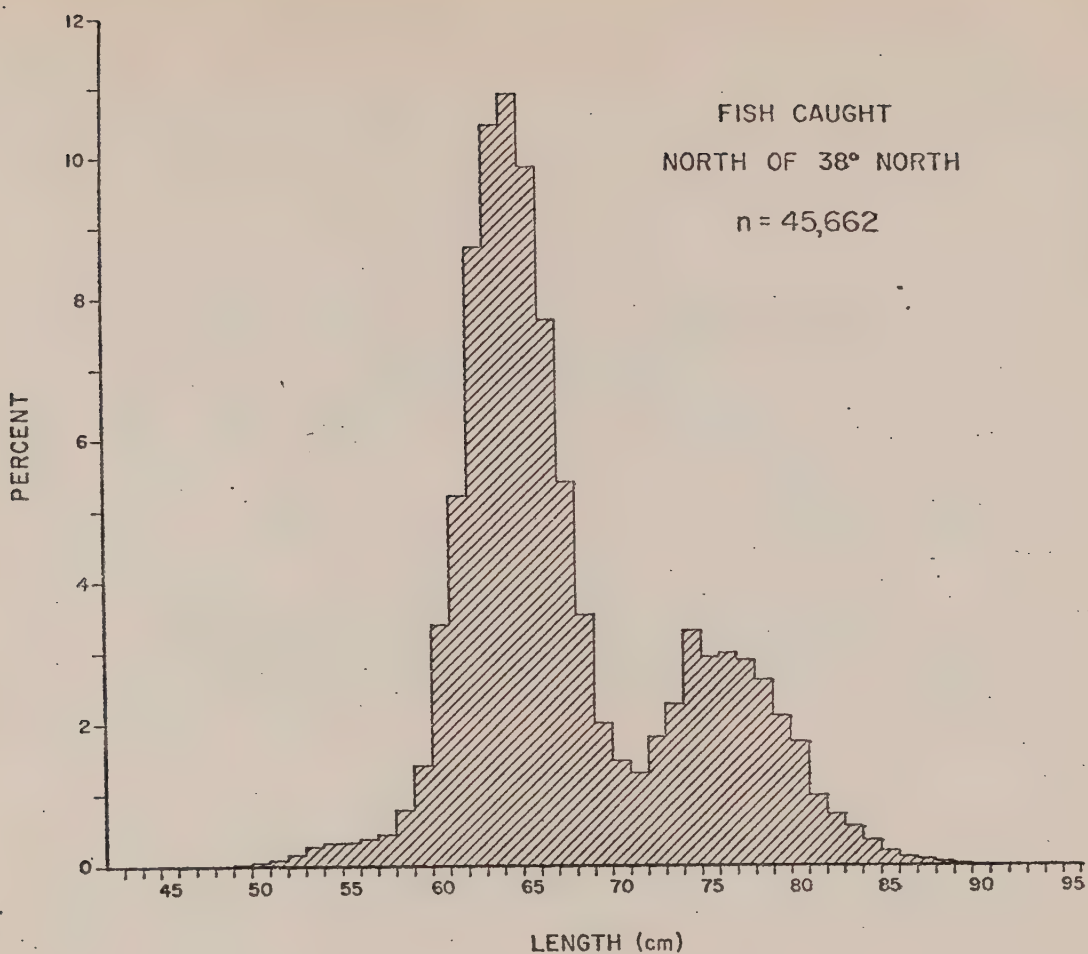


Figure 5.--Composite length-frequency distributions for North Pacific albacore caught north of 38°N and south of 38°N off the U.S. west coast during the 1972-75 fishing seasons.

FISHING SKIPJACK TUNA WITH NORTHERN ANCHOVY
IN HAWAIIAN WATERS

Second Trial, June 14-18, 1977

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July 1977

BAIT DISTRIBUTION

The Pacific Trojan arrived at Kewalo Basin, Honolulu, at 1645 on June 10, 1977 with approximately 400 scoops (3.6 kg (8 lb) per scoop) of northern anchovy, Engraulis mordax. The anchovy was captured 15-20 days previous. Two "aku boats" had been selected by drawing lots to receive the anchovy for field testing: the Lehua and the Anela. After considerable discussion, it was decided that the Lehua would first take on four solid baitwells of anchovy and the remainder would go to the Anela if sufficient amount of bait remained. Transferring of the anchovy, by bucket, took place on June 12. After transferring four wells, the Anela conceded her option because the remainder was insufficient for her. The Lehua took on six solid baitwells of anchovy, estimated at 50 buckets (9.1 kg (20 lb) per bucket).

The anchovy was judged to be in excellent condition. Approximately 60% of the anchovy was less than 7.6 cm (3 in.) in SL, with the remainder averaging 13 cm (5 in.).

FISHING OBSERVATIONS

Fishing trials commenced on June 14 and continued through June 18. Bait mortality for 7 days was estimated at 5%. Data were collected by observers from four trips in which the anchovy was used for skipjack tuna, Katsuwonus pelamis, fishing. Observational record forms were the same as used last year (Uchida 1976). For each school, the time of sighting, start of chumming, and the start and end of fishing were recorded. The amount of bait used per school, the number of men fishing, species caught, estimated average size of fish by school, estimated total catch, and reason for abandoning a school were recorded (Table 1). In addition, subjective observations on school behavior, bait behavior, and reaction of skipjack tuna (aku) to anchovy were noted.

FISHING RESULTS

During the four trips by the Lehua, a total of 20 schools was sighted of which 18 were chummed with anchovy, one school was chummed with nehu, Stolephorus purpureus, and one school was chummed with both nehu and anchovy. The results are summarized in Table 1. Remarks were also entered when external circumstances may have affected fishing.

In general, the average catch using anchovy alone compared favorably with the catches of other aku boats that had used nehu during the same period. Discounting fish caught on nehu, the Lehua averaged 1,770.9 kg (3,896 lb) for 3 effective fishing days and the remainder of the aku fleet

averaged 1,715.9 kg (3,775 lb) in 14 effective trips during the same 3 days of fishing. The average catch per effectively fished school by the Lehua amounted to 884.1 kg (1,945 lb). The catches from two other schools were not included because fishing was not fully pursued due to the small-sized fish.

Of 19 schools chummed with anchovy (nehu-anchovy included) 8 or 42% were successfully fished. The anchovy produced catch rates of 4.1 skipjack tuna per minute on fish larger than 7.7 kg (17 lb) and 9.2 fish per minute on fish smaller than 3.1 kg (7 lb) by an average of six fishermen. Chumming nehu and anchovy separately on one school of small skipjack tuna produced a catch rate of 19.6 skipjack tuna per minute with nehu (fished for 8 min) and 10.4 skipjack tuna per minute with anchovy (fished for 50 min). No comparison is possible with catch rates for the fleet during this period, but data from cannery landings and conversations with fishermen indicate that schools were few and generally slow biting.

For those schools successfully fished, 35 buckets (9.1 kg (20 lb) per bucket) of anchovy produced a total catch of 5,313.2 kg (11,689 lb) of skipjack tuna (Table 1). The catch per bucket amounted to 160.9 kg (354 lb), which is significantly higher than the catch of 104.1 kg (229 lb) per bucket recorded during similar trials conducted last year (Uchida 1976). In terms of total anchovy usage (including no-response chumming), catch per bucket was 118.2 kg (260 lb). The relatively more favorable result this year was probably attributable to the smaller size of anchovy (more individuals per school chummed) and to the presence of larger skipjack tuna that constituted 75% of the total catch by the Lehua. Cannery records for the 3 days show that large fish (larger than 6.8 kg (15 lb)) predominated in the catch--51.9% of the landings were large aku, 8.2% were medium aku (3.6-6.8 kg (8-15 lb)), and 39.9% were small aku (less than 3.6 kg (8 lb)). Last year, most of the fishing was conducted with larger anchovy on schools of small aku. Success rate was only 33% (7 of 21 schools chummed) as compared to 42% success this year.

OBSERVATION AND REMARKS

Anchovy and Skipjack Tuna Interaction

Anchovy, irrespective of size, tended to sound and disperse when chummed. A variety of fishing tactics was employed during fishing. None of the tactics, as chumming more anchovy, stunning the anchovy prior to chumming, stopping the vessel or doubling back on the school, resulted in improved fishing. During the chumming, only a few "surface breaks" were observed, indicating that the skipjack tuna were primarily

feeding below the surface. Reports from other vessels during this period indicated that aku schools were responding poorly to nehu, with the fish generally surfacing only for brief periods.

During the 5-day fishing trial period (four trips), Lehua ranked third among 11 boats in total catch (Table 2).

In general, Captain Kinney of the Lehua felt that catch rates would have been higher with nehu. The anchovy did not draw the fish to the stern like the commonly used nehu. On the positive side, the Lehua spent only 4 h on baiting operations during the 7-day period, including 2 h on the final day to catch six buckets of nehu to supplement the remaining anchovy.

Captain Kinney expressed the opinion (in common with other captains interviewed) that he would use anchovy, particularly when nehu was scarce, but only if the cost were considerably lower than the projected \$20 per bucket.

Assuming all fish were sold to the cannery, approximately 30% of the catch revenues would have gone for bait costs at \$20 per bucket. However, taking into consideration the generally poor catches for the entire fleet during the trial period, it is probable that catch per bucket (and profitability) would increase during normal "season" fishing.

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Table 1.--Fishing results.

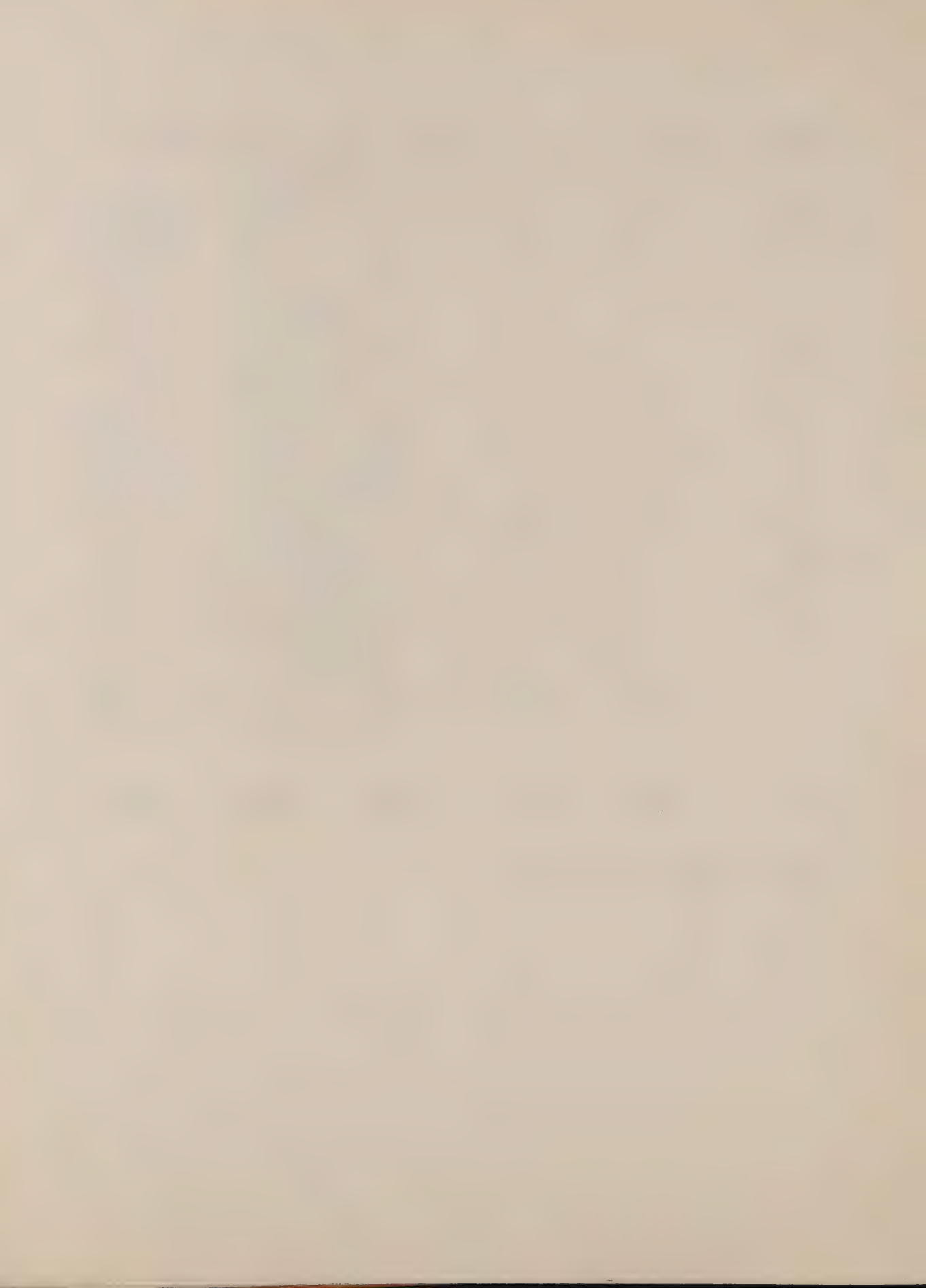
<u>Time Per School</u>		<u>Species</u>	<u>Size Range</u>	<u>Bait Used</u>		<u>Amount</u>	<u>ST</u>
<u>Chumming</u>	<u>Fishing</u>			<u>Predominant Size</u>			
<u>Min</u>	<u>Min</u>		<u>Cm</u>	<u>Cm</u>	<u>In.</u>	<u>Bkt</u>	
8		Anchovy		12.7	5	.15	
1		Anchovy		12.7	5	.05	
40		Anchovy		12.7	5	3.50	
18		Anchovy		12.7	5	.30	
25		Anchovy		12.7	5	2.00	
30	22	Anchovy		12.7	5	3.00	1
15	5	Anchovy		7.6	3	.25	
8	2	Anchovy		7.6	3	.25	
23	17	Anchovy		7.6	3	5.00	1
17	14	Anchovy	7.6-12.7	7.6	3	5.00	1
17	14	Anchovy	7.6-12.7	12.7	5	4.00	1
8		Anchovy	7.6-12.7	12.7	5	.25	
10		Anchovy	7.6-12.7	12.7	5	1.00	
8		Anchovy	7.6-10.1	10.1	4	.25	
3		Anchovy	7.6-10.1	10.1	4	.25	
42	29	Anchovy	5.1-10.1	10.1	4	8.00	2
18		Anchovy	5.1-10.1	5.1	2	2.00	
8		Anchovy	5.1-10.1			.25	
28	27	Nehu				1.75	
11	8	Nehu				2.00	
50	50	Anchovy	5.1-10.1			8.50	2

<u>Kipjack Tuna</u>		<u>Reason School</u> <u>Abandoned</u>	<u>Remarks</u>
<u>Lb</u>	<u>Avg Lb</u>		
		No response	
		No response	
		No response	
		No response	
		No response	
710	18	Biting stopped	
16	4	Small fish	
4	4	Small fish	
136	(18) (4)	Biting stopped	
818	18	Biting stopped	
241	17	Biting stopped	
		No response	
		No response	
		No response	
		No response	
916	18	Biting stopped	Blood entering water
		No response	
		No response	
738	6	Biting stopped	Problem with spray
864	5.5		Same school
848	5.5	Biting stopped	

Table 2.--Comparative catch in pounds per boat by Hawaiian skipjack tuna fleet during Lehua anchovy fishing trials.

<u>Vessel #</u>	<u>7/14</u>	<u>7/15</u>	<u>7/16</u>	<u>7/18</u>	<u>Total</u>
I	5,199	3,916	2,994	9,454	21,654
II	12,290	*	*	8,020	20,310
<u>Lehua</u>	0	6,189	2,868	3,834	12,891
IV	1,709	1,462	2,215	3,669	9,055
V	2,557	*	897	3,714	7,168
VI	3,307	*	3,664	*	6,971
VII	*	4,850	*	*	4,850
VIII	*	3,626	*	*	3,626
IX	*	3,572	*	*	3,572
X	0	*	708	*	708
XI	<u>403</u>	<u>*</u>	<u>*</u>	<u>*</u>	<u>403</u>
 TOTAL	 <u>25,462</u>	 <u>23,615</u>	 <u>13,346</u>	 <u>28,782</u>	 <u>91,208</u>

*Indicates baiting or zero catch.



BFISH: A POPULATION DYNAMICS
AND FISHERY MANAGEMENT MODEL

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I. INTRODUCTION

The BFISH computer model was initiated to lend insight into the possible effects of alternative fishery management schemes on the time dependent population sizes and geographical distributions of a variety of species of fish, and on some return function associated with those populations. BFISH is a multi-compartment, multi-species simulation model incorporating birth, death, and intercompartmental migration for each species. Several alternative management schemes have been internalized, others may be investigated by manipulation of the time dependent input coefficients. The return function presently incorporated is the fishing yield (in numbers of fish).

Specifically addressed are the attributes of the Hawaiian tuna and billfish fishery, but the model is constructed in a general nature, with the user supplying the compartmental structure and species characteristics. Thus, application to alternative management situations should yield excellent results providing the attributes of the problem are compatible with the assumptions made in the BFISH numerical formulation.

II. NUMERICAL FORMULATION

A. Population Dynamics

The geographical and chronological variations in fish populations are numerically modeled by discretizing the populations in space and time. Geographical compartments are set up by the user, and BFISH calculates the populations in each compartment at discrete, user-specified time intervals. For each species, a single age-class model is utilized that incorporates birth and death in each compartment and migration between compartments.

Numerically, the population dynamics problem is formulated as follows:

$$\begin{aligned} \frac{dP_{ij}(t)}{dt} = & - \left(FC_{ij}(t) + FS_{ij}(t) + XN_j + EM_{ij}(t) \right) P_{ij}(t) \\ & + SUM_{ij}(t) + RC_{ij}(t) \end{aligned} \quad (1)$$

where

$$FC_{ij}(t) = EC_i(t) * QC_{ij}(t)$$

$$FS_{ij}(t) = ES_i(t) * QS_{ij}(t)$$

$$EM_{ij}(t) = \sum_{k \neq i} XM_{i \rightarrow k, j}(t)$$

$$SUM_{ij}(t) = \sum_{k \neq i} XM_{k \rightarrow i, j}(t) * P_{kj}(t)$$

$$RC_{ij}(t) = FR_{ij}(t) * RP_j(t - m_j) * \left(\sum_k P_{kj}(t - m_j) \right)$$

and

$EC_i(t)$ = commercial fishing effort in compartment i at time t .

$ES_i(t)$ = sport fishing effort in compartment i at time t .

$FC_{ij}(t)$ = commercial fishing mortality coefficient for species j
in compartment i at time t .

$FS_{ij}(t)$ = sport fishing mortality coefficient for species j in
compartment i at time t .

$P_{ij}(t)$ = population of species j in compartment i at time t .

$QC_{ij}(t)$ = commercial fishing catchability coefficient for species j
in compartment i at time t .

$QS_{ij}(t)$ = sport fishing catchability coefficient for species j in
compartment i at time t .

$RC_{ij}(t)$ = recruitment rate to species j in compartment i at time t .

$RP_j(t)$ = reproduction coefficient for species j at time t .

$XM_{i \rightarrow k, j}(t)$ = migration coefficient for species j migrating from
compartment i to compartment k at time t .

XN_j = natural mortality coefficient for species j .

$FR_{ij}(t)$ = fraction of new recruits to species j at time t that will
be recruited to compartment i .

m_j = maturation age (age when fish enter the fishery) for species j .

The BFISH model incorporates the concept of a time cycle equal to some integral number of discrete time intervals, or timesteps. The user specifies the length of each timestep and the number of timesteps in each cycle. The input time dependent coefficients are

then characterized by the user for the first cycle, and BFISH repeats the values each succeeding cycle. An obvious time structure would be to use annual cycles with weekly, monthly, or quarterly timesteps depending on the availability of data and desired output resolution. By characterizing the necessary coefficients over a single cycle, calculations may proceed over any number of desired cycles without additional user involvement. The option exists, of course, to set up a single-cycle simulation, with the cycle being arbitrarily long. This would require, however, characterization of the time dependent coefficients over the entire span of the simulation, which could be very tiresome. The cycle concept takes advantage of the cyclical nature of such activities as spawning and migration to economize on input labors without reducing the model's capabilities.

Note that the recruitment rate to a given species at any time t is a function of the total population of that species at some prior time (= the maturation age of that species). That is, no geographical effect on spawning activity is accounted for, as the distribution of the fish at time of spawning ($t = t_s$) does not affect the total number of recruits at time $t = t_s + m_j$. Presently, the new recruits to species j are distributed to the various compartments based upon the fraction of the total population of species j that resides in each compartment at the beginning of the timestep being calculated, i.e.,

$$FR_{ij}(t) = \frac{P_{ij}(t_o)}{\sum_i P_{ij}(t_o)} (t_o \leq t \leq t_1) \quad (2)$$

t_0 = time at beginning of present timestep.

t_1 = time at end of present timestep.

No species interactions are modeled, hence the equations for each species may be solved independently. In the following discussion the subscript j is dropped for clarity, with the understanding that the equations apply to and are solved for each species in turn. The intercompartmental migration coefficients are coupling agents between the population equations for each compartment. Thus, equation (1) describes a system of N (N = number of compartments) coupled differential equations for each species:

$$\frac{d\bar{P}}{dt} = A\bar{P} + \bar{K} \quad (3)$$

where

$\bar{P}$ = a column vector of compartment populations, i.e.,

$$\bar{P} = \begin{bmatrix} P_1(t) \\ P_2(t) \\ \cdot \\ \cdot \\ \cdot \\ P_N(t) \end{bmatrix}$$

A = ($N \times N$) matrix with the migration coefficients in the off-diagonal elements.

$$A = [a_{ik}]$$

where

$$a_{ii} = -(\text{FC}_i(t) + \text{FS}_i(t) + \text{XN} + \text{EM}_i(t))$$

$$a_{ik} = \text{XM}_{k \rightarrow i}(t)$$

and $\bar{K}$ is a column vector of recruitment rates to each compartment, i.e.,

$$k_i = \text{FR}_i(t) * \text{RP}(t - m) * \left(\sum_{\ell=1}^N P_{\ell}(t - m) \right)$$

B. Yield Equations

The commercial and sport fishing yields of species j in compartment i during the time interval from t_0 to t_1 can be expressed:

$$\text{YELDC}_{ij}(t_0, t_1) = \int_{t_0}^{t_1} \text{EC}_i(t) * \text{QC}_{ij}(t) * P_{ij}(t) dt \quad (4)$$

$$\text{YELDS}_{ij}(t_0, t_1) = \int_{t_0}^{t_1} \text{ES}_i(t) * \text{QS}_{ij}(t) * P_{ij}(t) dt \quad (5)$$

where

$\text{YELDC}_{ij}(t_0, t_1)$ = commercial fishing yield of species j in compartment i over the time interval from t_0 to t_1 .

$\text{YELDS}_{ij}(t_0, t_1)$ = sport fishing yield of species j in compartment i over the time interval from t_0 to t_1 .

III. NUMERICAL SOLUTION

A. Population Dynamics

The population dynamics problem equation (3) is solved using a fourth order Runge-Kutta numerical integration scheme. If we denote the right-hand side of equation (3) by $f(\bar{P}, t)$, we have for compartment i :

$$\frac{dP_i}{dt} = f(P_1(t), P_2(t), \dots, P_N(t), t) \quad (6)$$

where the species subscript j is dropped for clarity. The computing procedure for the fourth order Runge-Kutta integration of equation (6) involves the use of four auxiliary quantities $XK1_i$, $XK2_i$, $XK3_i$, and $XK4_i$. If we know $P_i(t_0)$, we calculate $P_i(t_1)$ from

$$P_i(t_1) = P_i(t_0) + \frac{1}{6}(XK1_i + 2*XK2_i + 2*XK3_i + XK4_i) \quad (7)$$

where

$$XK1_i = H*f(P_1(t_0), P_2(t_0), \dots, P_N(t_0), t_0)$$

$$XK2_i = H*f\left(P_1(t_0) + \frac{XK1_1}{2}, \dots, P_N(t_0) + \frac{XK1_N}{2}, t_0 + \frac{H}{2}\right)$$

$$XK3_i = H*f\left(P_1(t_0) + \frac{XK2_1}{2}, \dots, P_N(t_0) + \frac{XK2_N}{2}, t_0 + \frac{H}{2}\right)$$

$$XK4_i = H*f\left(P_1(t_0) + XK3_1, \dots, P_N(t_0) + XK3_N, t_0 + H\right)$$

$$H = t_1 - t_0$$

The stability and accuracy of this method are dependent upon the timestep size H . In general, the timestep size should be sufficiently small so that the higher order terms (order > 4) neglected in the solution scheme are negligible. In practice, it is very difficult to know a priori what timestep size to assign a given BFISH analysis. Indeed, at times the timestep size will not be arbitrary, but will have a lower bound imposed by available data. For these reasons, it was considered appropriate to monitor the calculations as they proceed. This is done by calculating and printing out the Collatz coefficient of "sensitiveness":¹

$$S_i = \frac{XK2_i - XK3_i}{XK1_i - XK2_i} \quad (8)$$

A reasonable timestep size will yield a value of S close to unity. If S is too much larger than unity, a smaller timestep size is desirable. If S is too much smaller than unity, a larger timestep size may allow the user to decrease computational costs while maintaining desired accuracy. Validation runs with the BFISH model yield excellent agreement with exact analytical results for $S \leq 0.5$, and this value is suggested as a rule of thumb. However, S values of twice that size can be tolerated with only minimal loss of accuracy ($\sim 5\%$).

¹Collatz, Lothar. 1966. The numerical treatment of differential equations. Springer-Verlag, New York, Inc., N.Y., 568 p.

B. Yield Equations

The numerical technique used to calculate the fishing yields is presented here in terms of a general yield function. Specific application to commercial and sport fishing yields in the BFISH model merely requires the appropriate effort and catchability coefficient functions.

The general yield function, Y , for a given species and compartment, is defined by:

$$Y(t) = E(t) * Q(t) * P(t) \quad (9)$$

$E(t)$ = fishing effort

$Q(t)$ = fishing catchability coefficient

$P(t)$ = fish population

The fishing yield over some time interval (t_0, t_1) will be the integral of equation (9) over the interval:

$$YIELD = \int_{t_0}^{t_1} Y(t) dt = \int_{t_0}^{t_1} E(t) * Q(t) * P(t) dt \quad (10)$$

If we assume that $Y(t)$ on the interval can be represented by a third order Taylor series expansion about t_0 , we have

$$Y(t) = Y(t_0) + Y'(t_0)\Delta t + Y''(t_0)\frac{\Delta t^2}{2} + Y'''(t_0)\frac{\Delta t^3}{6} \quad (11)$$

for $(t_0 \leq t \leq t_1)$

$$\Delta t = t - t_0$$

which is easily analytically integrated to give:

$$\int_{t_0}^{t_1} Y(t) dt = Y(t_0)H + Y'(t_0)\frac{H^2}{2} + Y''(t_0)\frac{H^3}{6} + Y'''(t_0)\frac{H^4}{24} \quad (12)$$

where $H = t_1 - t_0$.

Thus, if equation (11) is an adequate representation of the yield function $Y(t)$ on (t_0, t_1) , and if we can characterize the expansion coefficients, the fishing yield over the interval can be easily calculated from equation (12).

Note that $E(t)$ and $Q(t)$ are input functions of time, and their values and derivatives are known for all time t . At the beginning of a timestep the population $P(t_0)$ is known, and by substitution into equation (3) $P'(t_0)$ is known. Similarly, at the completion of the Runge-Kutta calculations over the timestep $P(t_1)$ and $P'(t_1)$ will be known. Hence, we can easily calculate

$$Y(t_0) = E(t_0) * Q(t_0) * P(t_0) \quad (13)$$

$$\begin{aligned} Y'(t_0) = & E(t_0) * Q(t_0) * P'(t_0) + E(t_0) * Q'(t_0) * P(t_0) \\ & + E'(t_0) * Q(t_0) * P(t_0) \end{aligned} \quad (14)$$

$$Y(t_1) = E(t_1) * Q(t_1) * P(t_1) \quad (15)$$

$$\begin{aligned} Y'(t_1) = & E(t_1) * Q(t_1) * P'(t_1) + E(t_1) * Q'(t_1) * P(t_1) \\ & + E'(t_1) * Q(t_1) * P(t_1) \end{aligned} \quad (16)$$

By evaluating equation (11) and its first time derivative at the end of the timestep ($t = t_1$) we get

$$Y(t_1) = Y(t_0) + Y'(t_0)H + Y''(t_0)\frac{H^2}{2} + Y'''(t_0)\frac{H^3}{6} \quad (17)$$

$$Y'(t_1) = Y'(t_0) + Y''(t_0)H + Y'''(t_0)\frac{H^2}{2}$$

Since we know $Y(t_0)$, $Y'(t_0)$, $Y(t_1)$, and $Y'(t_1)$, equations (17) form a system of two equations in two unknowns ($Y''(t_0)$ and $Y'''(t_0)$). This system is solved to yield the recursion equations:

$$Y'''(t_0) = -\frac{12}{H^3} (Y(t_1) - Y(t_0)) + \frac{6}{H^2} (Y'(t_1) + Y'(t_0)) \quad (18)$$

$$Y''(t_0) = \frac{2}{H^2} (Y(t_1) - Y(t_0)) - \frac{H}{3} Y'''(t_0) - \frac{2}{H} Y'(t_0) \quad (19)$$

We can now complete the expansion equation (11) and calculate the integral equation (12).

This technique is generally applicable to any function on any interval (t_0, t_1) for which the appropriate boundary values and derivatives are known. Specifically, in BFISH, it is used in three different calculations. The first two are the yield function for commercial and sport fishing yields, respectively.

$$YIELD C = \int_{t_0}^{t_1} EC(t) * QC(t) * P(t) dt \quad (20)$$

YIELDC = commercial fishing yield

$$YIELDS = \int_{t_0}^{t_i} ES(t) * QS(t) * P(t) dt \quad (21)$$

YIELDS = sport fishing yield

These yields are calculated for each species and compartment over each timestep. The third application of the technique is in the recruitment calculation, which is discussed in the next section.

The basic assumption implicit in this technique is that the function to be integrated can be adequately described on the interval of interest by a third order Taylor series. Validation runs with BFISH are in excellent agreement with exact analytical results for timestep sizes which yield a Collatz coefficient $S \leq 0.5$. Thus, a high degree of accuracy can be maintained in both the Runge-Kutta and yield calculations by keeping S within the recommended range.

C. Recruitment

As was noted previously, the recruitment rate at time t is dependent upon the spawning population at some previous time $(t - m)$. Specifically, the recruitment rate for a given species at time t is given by

$$\left. \frac{dP(t)}{dt} \right|_{\text{RECRUITMENT}} = RP(t - m) * P_{\text{TOT}}(t - m) \quad (22)$$

RP = reproduction coefficient

P_{TOT} = total population

Thus, the total number of fish added to a population over an interval (t_0 , t_1) will be:

$$\Delta P = \int_{t_0}^{t_1} dP = \int_{t_0}^{t_1} RP(t - m) * P_{TOT}(t - m) dt \quad (23)$$

The BFISH model incorporates the concept of a recruitment period for each species. This is some arbitrary segment of each time cycle during which the fish are assumed to spawn. The maturation age, m , is input as the number of cycles between the time of spawning and the time when the new fish enter the fishery. Thus, spawning activity during the k^{th} timestep of cycle L will produce new recruits to the population during the k^{th} timestep of cycle $L + m$. The recruitment period itself is an arbitrary number of timesteps in length, and occurs at the same time each cycle. Numerically, the problem is to characterize the reproduction function, RPP, over the recruitment period for each cycle, and store the characterization for retrieval m cycles later, where

$$RPP(t) = RP(t) * P_{TOT}(t) \quad (24)$$

Using the same arguments as applied to the yield function, we know RPP and RPP' at the beginning and end of each timestep, and thus can calculate the integral of the function over the timestep in the same manner using a third order Taylor series. This integral, equation (23), is

evaluated for each timestep in the recruitment period. The total number of fish that will be added to the population by the recruitment mechanism m cycles later is

$$\bar{R} = \sum_{i=1}^{N_R} \Delta P = \sum_{i=1}^{N_R} \int_{t_{oi}}^{t_{li}} RP(t) * P_{TOT}(t) dt \quad (25)$$

N_R = number of timesteps in the recruitment period.

t_{oi} = time at beginning of timestep i in the recruitment period.

t_{li} = time at end of timestep i in the recruitment period.

Thus, at the end of each recruitment period, BFISH will have calculated:

$$RPP(t_I) = RP(t_I) * P_{TOT}(t_I) \quad (26)$$

$$RPP'(t_I) = RP(t_I) * P'_{TOT}(t_I) + RP'(t_I) * P_{TOT}(t_I) \quad (27)$$

$$RPP(t_F) = RP(t_F) * P_{TOT}(t_F) \quad (28)$$

$$RPP'(t_F) = RP(t_F) * P'_{TOT}(t_F) + RP'(t_F) * P_{TOT}(t_F) \quad (29)$$

$$\bar{R} = \int_{t_I}^{t_F} RPP(t) dt = \sum_{i=1}^{N_R} \int_{t_{oi}}^{t_{li}} RPP(t) dt \quad (30)$$

where t_I = time at the beginning of the recruitment period.

t_F = time at the end of the recruitment period.

Next, we assume that the function $RPP(t)$ can be represented over the entire recruitment period (t_I, t_F) by a fourth order Taylor series expansion about t_I :

$$\begin{aligned} RPP(t) = & RPP(t_I) + RPP'(t_I)\Delta t + RPP''(t_I)\frac{\Delta t^2}{2} + RPP'''(t_I)\frac{\Delta t^3}{6} \\ & + RPP^{(4)}(t_I)\frac{\Delta t^4}{24} \quad (t_I \leq t \leq t_F) \end{aligned} \quad (31)$$

$$\Delta t = t - t_I$$

Differentiating equation (31) with respect to time yields

$$RPP'(t) = RPP'(t_I) + RPP''(t_I)\Delta t + RPP'''(t_I)\frac{\Delta t^2}{2} + RPP^{(4)}(t_I)\frac{\Delta t^3}{6} \quad (32)$$

and integrating equation (31) over the recruitment period yields:

$$\begin{aligned} \bar{R} = & RPP(t_I)\Delta t_R + RPP'(t_I)\frac{\Delta t_R^2}{2} + RPP''(t_I)\frac{\Delta t_R^3}{6} \\ & + RPP'''(t_I)\frac{\Delta t_R^4}{24} + RPP^{(4)}(t_I)\frac{\Delta t_R^5}{120} \end{aligned} \quad (33)$$

where $\Delta t_R = t_F - t_I$

Note that we know $RPP(t_I)$, $RPP'(t_I)$, $RPP(t_F)$, $RPP'(t_F)$, and $\bar{R}$. Thus, by evaluating equations (31) and (32) at $t = t_F$, and augmenting the two resulting equations with equation (33), we have a system of 3 equations in 3 unknowns $(RPP''(t_I), RPP'''(t_I), \text{ and } RPP^{(4)}(t_I))$. This system can be solved to yield the recursion equations:

$$\begin{aligned}
 RPP^{(5)}(t_I) &= \frac{720}{\Delta t_R^5} \bar{R} - \frac{360}{\Delta t_R^4} (RPP(t_F) + RPP(t_I)) \\
 &\quad + \frac{60}{\Delta t_R^3} (RPP'(t_F) - RPP'(t_I))
 \end{aligned} \tag{34}$$

$$\begin{aligned}
 RPP^{(4)}(t_I) &= \frac{6}{\Delta t_R^2} (RPP'(t_F) + RPP'(t_I)) \\
 &= -\frac{12}{\Delta t_R^3} (RPP(t_F) - RPP(t_I)) - \frac{\Delta t_R}{2} RPP^{(5)}(t_I)
 \end{aligned} \tag{35}$$

$$\begin{aligned}
 RPP^{(3)}(t_I) &= \frac{2}{\Delta t_R^2} (RPP(t_F) - RPP(t_I)) - \frac{2}{\Delta t_R} RPP'(t_I) \\
 &\quad - \frac{\Delta t_R}{3} RPP^{(4)}(t_I) - \frac{\Delta t_R^2}{12} RPP^{(5)}(t_I)
 \end{aligned} \tag{36}$$

This completes the characterization of the Taylor series expansion of the reproduction function $RPP(t)$ over the recruitment period. The coefficients of the expansion are stored, and m cycles in the future, recalled. The recruitment rate at time t for a given cycle is then:

$$RC(t) = RPP(t - m) \quad t_I + m \leq t \leq t_F + m \tag{37}$$

$$RC(t) = 0 \quad t < t_I + m \tag{38}$$

$$t > t_F + m$$

The total recruitment rate for a given species is then divided among the compartments based upon the fraction of the total species population that resides in each at the beginning of the timestep.

D. Internal Management Schemes

The BFISH model has the capability of keeping separate population and yield totals for a user-specified management area, which is a subset of the total number of compartments used in the model. Commercial fishing effort for each compartment may be supplied by the user or calculated by BFISH. Within the management area, additional constraints may be placed upon the commercial fishing effort in the form of effort or yield ceilings. Some inter-species numerical coupling may exist as a result of the commercial fishing fleet keying on more than one species, or multi-species yield ceilings being specified by the user. As described below, when this coupling exists it is manifested during step changes in the applied effort function across timestep boundaries, and does not affect the solution procedure described earlier.

The options available to the user for the distribution of commercial fishing effort and the management of the managed area are described below:

1) MANAGEMENT OPTION 1

When the first management option is specified, the commercial fishing effort function must be supplied by the user for each compartment separately. A management area may be specified (some arbitrary subset of the total compartment set), for which population and yield subtotals will be kept, but no special calculations or constraints will be applied.

2) MANAGEMENT OPTION 2

When the second management option is specified, BFISH will internally calculate the commercial fishing effort in each compartment subject to an effort ceiling placed on each managed compartment. The user must supply the total commercial fishing effort function (total effort = effort summed over all compartments) and the effort ceiling function for each managed compartment.

The total commercial fishing effort function is utilized as a step function with the total effort assumed constant over each timestep. Hence, if we define

$TE(t)$ = total commercial fishing effort function supplied by the user

BFISH will calculate the total fishing effort to be divided up among the various compartments from:

$$\begin{aligned}
 TEFORT &= TE(t_1) & t_1 < t \leq t_2 \\
 TEFORT &= TE(t_2) & t_2 < t \leq t_3 \\
 &\vdots & \vdots \\
 &\vdots & \vdots \\
 &\vdots & \vdots \\
 TEFORT &= TE(t_k) & t_k < t \leq t_{k+1}
 \end{aligned} \tag{39}$$

where

$TEFORT$ = total commercial fishing effort used by BFISH

t_k = time at beginning of k^{th} timestep.

Thus, the total commercial fishing effort function supplied by the user differs from the other time dependent input functions in that it is never evaluated between timestep boundaries.

It is assumed that the commercial fishing fleet will key on the movements of their target species, and thus the most commercial effort will be found where there are the most fish. It is also assumed that the commercial fleet does not instantaneously recognize fish movement, and there exists a lag time between the real fish distribution and subsequent commercial fishing effort distribution. Consequently, the commercial fishing effort in each compartment for each timestep is calculated based on the total effort available for that timestep and the fraction of the total target population that resided in each compartment at the beginning of the previous timestep.

$$E_i(t) = \frac{PTARGET_i(t_{k-1})}{TTARGET(t_{k-1})} * TE(t_k) \quad (40)$$

$$t_k < t \leq t_{k+1}$$

$E_i(t)$ = commercial fishing effort applied to compartment i
at time t

t_k = time at beginning of timestep k

$PTARGET_i(t)$ = target population in compartment i at time t

$$TTARGET(t) = \sum_i PTARGET_i(t)$$

Note that $E_i(t)$ is constant over each timestep with step changes at the timestep boundaries. The target population may be composed of one or several constituent species. Thus, the movement of the commercial fishing fleet may be modeled as a function of the movement of the target

species of fish. If this is all that is required, the user would specify a null set of managed compartments. If, however, a management area is used, then the compartments within the managed area are subject to the additional constraint of user-supplied effort ceilings.

$$CEILNG_i(t) = CL_i(t_k) \quad t_k < t \leq t_{k+1} \quad (41)$$

$CL_i(t)$ = ceiling function for compartment i evaluated at time t

$CEILNG_i(t)$ = effort ceiling used by BFISH for compartment i at time t

Note that the effort ceiling function, like the total effort function, is used as a step function constant across each timestep. The commercial fishing effort calculation will then proceed as follows:

- a) Calculate the commercial fishing effort in each compartment from equation (40).
- b) Check each managed compartment to see if the calculated fishing effort exceeds the effort ceiling for that compartment.
- c) If the calculated effort exceeds the ceiling, set the effort equal to the ceiling and save the amount of excess effort that must be distributed elsewhere. Remove the compartment from further calculation.
- d) After (b) and (c) have been completed for all compartments, distribute the accumulated excess effort among the compartments still in the calculation based on their respective target populations.
- e) Go back to (b).

This iterative process continues until there is no more excess effort at the end of step (c).

3) MANAGEMENT OPTION 3

When the third management option is specified, BFISH will again internally calculate the distribution of the total commercial fishing effort from equation (40), except that a yield ceiling is placed on each compartment in the management area. This yield ceiling is not time dependent, and is used as a cycle-to-date yield limit. Thus, compartment i is removed from the calculations if

$$YMANAG_i(t_k) \geq YCEILNG_i$$

$YMANAG_i(t)$ = total commercial fishing yield of managed species
taken during the present time cycle in compartment i
up to time t .

t_k = time at the beginning of the k^{th} timestep.

$YCEILNG_i$ = cycle-to-date yield ceiling for compartment i

The managed species may be all the species modeled or some subset thereof. Note that the cycle-to-date yield is checked and the effort is distributed at the beginning of each timestep. It is therefore possible for the commercial fishing yield in a managed compartment to be less than the applied ceiling at the beginning of the timestep, and exceed the ceiling during the timestep. This will be flagged at the beginning of the next timestep, and no more commercial fishing effort will be applied to that compartment for the remainder of the time cycle. Naturally, all cycle-to-date totals are reset to zero at the beginning of each time cycle.

For the third management option, the user must supply the total commercial fishing effort function, the constituent compartments in the management area, the yield ceiling for each managed compartment, the constituent species in the target fish population, and the constituent species in the managed fish population.

IV. INPUTS

A. General Information

The majority of the inputs required to run a BFISH analysis are characterizations of the time dependent coefficients. As mentioned earlier, these functions need only be characterized over the first time cycle, and are repeated for each subsequent cycle. Thus, one must completely describe each time dependent input function over the interval from (time = zero) to (time = end-of-cycle). Using f as a general function for demonstration purposes, we must describe

$$f(t) \quad 0 \leq t \leq t_F$$

where t_F = time at end-of-cycle

There are two alternative ways to describe $f(t)$ over the cycle available to the BFISH user. First, if $f(t)$ is smooth and well-behaved, it might be possible to represent f as a polynomial in time:

$$\begin{aligned} f(t) &= a_1 + a_2 t + a_3 t^2 + \dots a_{n+1} t^n \\ &= \sum_{i=0}^n a_{i+1} t^i \\ &(0 \leq t \leq t_F) \end{aligned} \tag{42}$$

In this case the user need only specify n , the order of the polynomial, and the $(n + 1)$ coefficients a_i .

The second type of representation is to specify explicitly what value $f(t)$ is to take at the timestep boundaries. BFISH will then treat $f(t)$ as a piecewise linear function with as many "pieces" as there are timesteps. The value of $f(t)$ at any time during the timestep will fall along the line connecting the user supplied values at the timestep boundaries. For example, $f(t)$ would be evaluated on (t_k, t_{k+1}) from

$$f(t) = f(t_k) + \left[\frac{t - t_k}{t_{k+1} - t_k} \right] * \left[f(t_{k+1}) - f(t_k) \right] \quad (t_k \leq t \leq t_{k+1}) \quad (43)$$

where

$f(t_k)$ = user supplied value of $f(t)$ at the beginning of the k^{th} timestep

t_k = time at the beginning of the k^{th} timestep.

The end-of-timestep value for any timestep is the same as the beginning-of-timestep value for the next timestep. Thus, by supplying the beginning of timestep values for each timestep in the cycle, a continuous piecewise linear function is completely described across the cycle.

When describing an input function, the input card is, in general, utilized as follows:

COLS 1 - 3 : species number

COLS 4 - 6 : compartment number

COLS 7 - 9 : type of representation

(1 = polynomial)

(2 = explicit)

COLS 10 - 12 : order of the polynomial (if type 1) or card number

(if type 2)

COLS 13 - 23	}	
24 - 34		
35 - 45		fixed decimal input values for polynomial coefficients
46 - 56		(if type 1) or modal values (if type = 2).
57 - 67		
68 - 78		

Thus, columns 1-12 hold four integer variables of field width 3, and columns 13-78 hold six fixed decimal variables of field width 11. This breakdown is reflected in the standard BFISH coding form shown in Figure 1.

As an example of a polynomial input, assume we wish to represent $f(t)$ as a fourth order polynomial:

$$f(t) = 5. + 0.06 t - 0.7 t^3 + 0.0006 t^4 \quad (44)$$

$$(0 \leq t \leq t_F)$$

where $f(t)$ describes some time dependent coefficient for species 1 and compartment 3. In general, the species will be specified once and need not be repeated for all inputs pertaining to that species. Assume this has been done on some previous card. The necessary input card representing $f(t)$ would then appear as in Figure 2A. Note that the compartment number, type of representation, order of the polynomial, and the polynomial coefficients all appear on the same input card. This format is characteristic of polynomial (type 1) variables. Since there is space on each card for 6 fixed decimal coefficients, the user is limited to polynomials of order 5 or less. The effort ceiling polynomial, as noted below, is restricted to order 4 or less.

Figure 1.--BFISH coding form.

[illegible]

Now suppose the user has decided to break up each cycle into 10 timesteps, and wishes to represent $f(t)$ over each cycle as shown in Figure 3. In this case f would be explicitly represented (type 2) and the necessary input cards would be as shown in Figure 2B. Note that the set of cards with the input nodal values follows the card describing the compartment number and type of representation, each card containing nodal points is numbered, and a maximum of four nodal values appears on each card. These characteristics will always be true for explicit (type 2) variables. The number of timesteps per cycle, and hence the number of cards necessary to list all the nodal values, is arbitrary, but a nodal value must appear for each timestep.

B. Input Deck Format

The format for the input deck necessary to run a BFISH analysis is shown in Figure 4, which is discussed in the following paragraphs.

1. Model structure

The first two cards of any BFISH input deck set up the model structure. Referring to Figure 4, we have:

NSP = number of species (≤ 3)
 NCM = number of compartments (≤ 50)
 NCY = number of cycles to be modeled
 NST = Number of timesteps per cycle
 H = length of each timestep

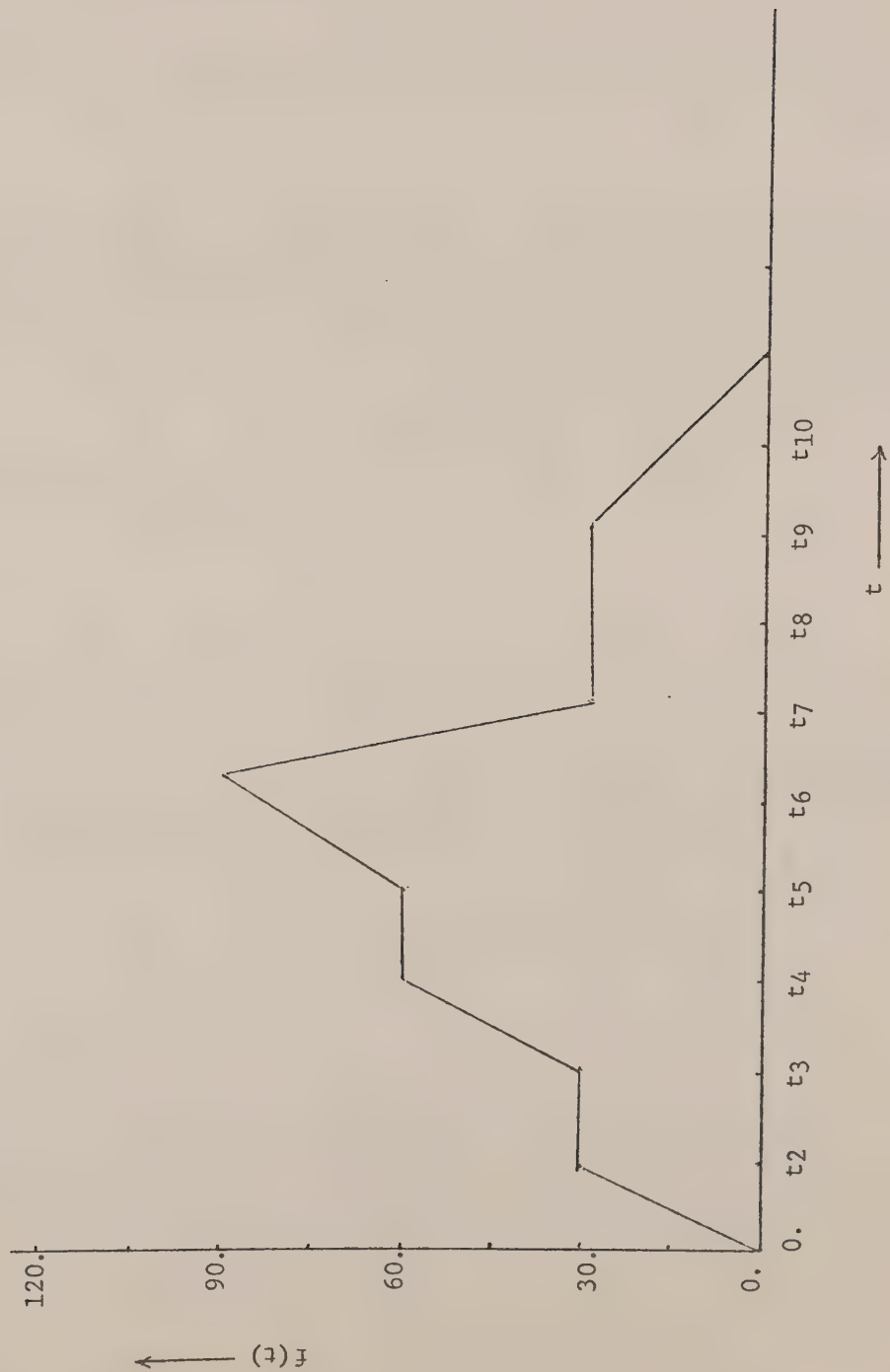


Figure 3.--Time dependence of $f(t)$.

Figure 4.--BFISH input format.

MODEL STRUCTURE INPUTS:

[illegible]

IF MOPT = 1

FOR EACH COMPARTMENT (i = 1 to NCM): COMMERCIAL FISHING EFFORT INPUTS

[illegible]

IF MOPT = 2:

TOTAL COMMERCIAL FISHING EFFORT INPUTS:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
						T			0 ¹	coefficients ¹																																								
									cd ²	nodal values ²																																								

FOR EACH MANAGED COMPARTMENT (k = 1 to NMC): EFFORT CEILING INPUTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
						C_k							T_k	0^1	coefficients																																			
														cd^2	nodal values																																			

IF MOPT = 3:

TOTAL COMMERCIAL FISHING EFFORT INPUTS:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51		
						T	0 ¹	coefficients ¹ →																																												
							cd ²	nodal values ² →																																												

FOR EACH MANAGED COMPARTMENT ($k = 1$ to NMC): YIELD CEILING

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	
						C_k																																													

FOR EACH COMPARTMENT ($i = 1$ to NCM): SPORT FISHING EFFORT INPUTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51			
						C_i	T_i	0	coefficients ¹ →																																												
								cd ²	nodal values ² →																																												

Figure 4.--Continued.

FOR EACH SPECIES ($j = 1$ to NSP):

RECRUITMENT AND NATURAL MORTALITY INPUTS:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
S _j			R1 _j			R2 _j			m _j			XN _j																																			

REPRODUCTION COEFFICIENT INPUTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50		
						T_j	0^1	coefficients ¹ $\longrightarrow$																																											
							cd^2	nodal values ² $\longrightarrow$																																											

FOR EACH COMPARTMENT (i = 1 to NCM):

COMMERCIAL FISHING CATCHABILITY COEFFICIENT-INPUTS:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
						C_i	T_{ij}	0^1	coefficients ¹ $\longrightarrow$																																			
								cd^2	nodal values ² $\longrightarrow$																																			

FOR EACH COMPARTMENT ($i = 1$ to NCM):

SPORT FISHING CATCHABILITY COEFFICIENT INPUTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
C _i						T _{ij}		0 ¹	coefficients ¹ →																																				
								cd ²	nodal values ² →																																				

Figure 4.--Continued.

FOR EACH COMPARTMENT (I = 1 to NCM):

MIGRATION INPUTS

[illegible]

FOR EACH COMPARTMENT MIGRATED TO ($k = 1$ to $MT0_{ij}$)

MIGRATION COEFFICIENT INPUTS:

[illegible][illegible]

NMC = number of managed compartments ($\leq$ NCM)

(= number of compartments in the management area)

MOPT = management option

(= 1, 2, or 3)

IK = target species key (IK is only required when MOPT = 2 or 3),

where

IK = 1 → the target population includes only species 1

IK = 2 → the target population includes species 1 and species 2

IK = 3 → the target population includes species 1, 2, and 3.

IY = yield limit key (IY is only necessary if MOPT = 3), where

IY = 1 → managed yield = yield of species 1.

IY = 2 → managed yield = yield of species 1 plus the yield of
species 2.

IY = 3 → managed yield = yield of species 1 plus yield of species 2
plus yield of species 3.

IY = 4 → managed yield = yield of species 2 plus yield of species 3.

Only the commercial fishing yield is counted toward the yield limit.

Thus, if we want the commercial fishing fleet to key on a target population consisting of the summed population of three different species, but our management scheme calls for an upper limit on the number of fish that can be taken commercially from species number 1 only within our management area, we would set MOPT = 3, NSP = 3, IK = 3, and IY = 1.

2. Commercial fishing effort and ceiling inputs

This section of the input deck follows the two model structure cards, and will differ in format for different management options. The three alternative (and mutually exclusive) formats are:

- a) If MOPT = 1, the commercial fishing effort must be supplied for each compartment separately. Referring to Figure 4, we define:

C_i = compartment number

T_i = type of representation (1 or 2, for polynomial or explicit representation, respectively)

O = order of the polynomial

cd = card number

The superscript 1 denotes variables that are only required if $T = 1$, and the superscript 2 denotes variables that are only required if $T = 2$. The first NMC compartments listed will constitute the management area. No special calculation will take place for the managed compartments, but separate population and yield sub-totals will be kept for the management area. Compartment numbers must range from 1 to NCM, but need not be listed in order. If $T = 2$ for any compartment, NST nodal values must be listed, four to a card. Obviously, if $NST > 4$, there will be more than one card involved in supplying all NST nodal values. Each of these cards is numbered.

- b) If $MOPT = 2$, the user must supply the total commercial fishing effort function and, for each managed compartment, the effort ceiling function. Effort ceiling inputs must be supplied for NMC compartments. Any compartment number not specified in the effort ceiling input set is assumed to be out of the management area (and hence has no effort ceiling). Thus, if $NCM = 10$ and $NMC = 3$, three effort ceiling functions must be supplied. Suppose the three C_k supplied are 4, 7, and 9. Then compartments 4, 7, and 9 constitute the management area. Compartments 1, 2, 3, 5, 6, 8, and 10 are unmanaged. If $T = 1$, 0 for the effort ceiling function must be ≤ 4 .
- c) If $MOPT = 3$, the total commercial fishing effort function is again required. In addition, the user must supply the yield ceiling placed on each managed compartment. This is a single quantity, not a function, and is specified by Y_k for compartment C_k in Figure 4. If the total commercial fishing yield (of the species specified by IY) in compartment C_k ever exceeds Y_k during any one time cycle, commercial fishing effort in C_k is set to zero for the remainder of the cycle.

3. Sport fishing effort inputs

For each compartment, the sport fishing effort function is specified.

4. Species dependent inputs

The following input requirements describe the species dependent inputs for a single species. The species number for each set is specified as the first card of the set. NSP such sets must be supplied, one for each species.

a) Recruitment and natural mortality

Referring to Figure 4, the following definitions are made:

S_j = species number

$R1_j$ = first timestep in the recruitment period for species S_j

$R2_j$ = last timestep in the recruitment period for species S_j

m_j = maturation age (in number of cycles) for species S_j

XN_j = natural mortality coefficient for species S_j .

b) Reproduction coefficient

The reproduction coefficient function is supplied for species S_j . Note that this function is only evaluated during the recruitment period for species S_j , and hence must only be valid on the interval (t_{R1_j}, t_{R2_j+1}) .

c) Commercial fishing catchability coefficient

This variable is both species and compartment dependent. The commercial catchability coefficient function is supplied for each compartment C_i for each species S_j .

d) Sport fishing catchability coefficient

This function is supplied for each compartment C_i for each species S_j .

e) Migration coefficients

The format for these inputs differs slightly from the other functional inputs. For each species S_j a migration set is described for each compartment C_i . Referring to Figure 4, the following definitions apply:

T_{ij} = type of function representation for species S_j and compartment C_i (= 1 or 2).

MTO_{ij} = the number of different compartments that species S_j migrates to from compartment C_i during the course of a time cycle (≤ 8).

POP_{ij} = initial population of species S_j in compartment C_i .

Then, for $k = 1, MTO_{ij}$, the migration coefficient functions are supplied, where:

CTO_{ijk} = the compartment number of the k^{th} compartment migrated to by species S_j from compartment C_i .

If $T_{ij} = 1$, CTO_{ijk} is followed by the order of the polynomial and the polynomial coefficients to describe the time dependence of the migration coefficient for species S_j migrating from compartment C_i to compartment CTO_{ijk} . If $T_{ij} = 2$, card number one of the nodal set follows on the same card as CTO_{ijk} . If additional cards are required ($NST > 4$), CTO_{ijk} is repeated on each card in addition to supplying the card number and the next 4 nodal values.

5. End of file

A star ('*') is placed in column one of an otherwise blank card to denote the end of the input data for the BFISH program. This card is placed immediately after the last card in the input deck, but before any additional record or file marks required by the operating system.

C. Rules for coding

BFISH is written in FORTRAN, and there are some characteristics common to most FORTRAN compilers that are relevant to the input file format. Specifically:

1. Right adjust all integer variables. FORTRAN will add zeroes to fill up the field. For example, if the species number, $S_j = 3$, is punched in column 2 instead of column 3 of the appropriate input card, BFISH will read it as $S_j = 30$. Thus, all values appearing in the four integer fields (columns 1-3, 4-6, 7-9, and 10-12) should be right adjusted.

2. Blanks are interpreted as zeroes. Thus, leaving any field blank is equivalent to giving that variable a value of zero.

3. Decimals must be supplied to fixed decimal inputs. It is possible, but not probable, that the value will be interpreted correctly if the decimal is omitted. The issue can be avoided by supplying decimals in the proper places in all values punched in fixed decimal fields (columns 13-23, 24-34, 35-45, 46-56, 57-67, and 68-78).

V. OUTPUT

A. Echo Check

The first section of the BFISH output file is a complete list of all the input parameters with each value associated with its function in the program. These values should be carefully checked to see if the user's intentions have been accurately transmitted to the BFISH model. It is expected that most of the problems that arise in using the model will be at the input level, and the echo section of the output should be scrutinized for accuracy each time the model is employed.

BFISH reads in the nodal points of explicitly represented variables, in groups of 4, as they are needed during execution. Thus, not all points are kept in storage (if $NST > 4$) at any one time. These nodal points are printed out as they are read. The first four points appear in the echo section. Any additional points are identified and printed out as they are read during execution. Thus, the timestep output may be intermittently interrupted to print out sets of nodal points as they are needed.

B. Timestep Output

The timestep output is printed out at the end of each timestep. This is an important consideration, as BFISH contends with discontinuous functions (e.g., commercial fishing effort when $MOPT = 2$ or 3) and discontinuous first derivatives (e.g., any explicitly represented variable) across timestep boundaries. The values printed at time t are consistent with an incremental approach to t from the negative side (i.e.,

are equivalent to the appropriate values at time $(t - \epsilon)$ where ϵ is arbitrarily small).

First the time is identified by the following four variables:

ICYCLE = time cycle number

ISTEP = timestep number within this cycle

TIME = time expired within this cycle

TTOTAL = total time expired

The fishing population and yield outputs are then presented for each species in turn. Within each species set, the fishing efforts, catchability coefficients, recruitment rates, populations, and yields are printed for each compartment. In addition, the Collatz coefficient, S , is printed for each compartment for the calculation just completed. This coefficient is defined by equation (8), and should be used as a measure of the appropriateness of the timestep size. If the population gradient is zero, equation (8) will be undefined, and S is set equal to -1.

Each species set continues with a printout of the population and yields summed over all compartments and summed over the management area. Cycle-to-date yields are also calculated and printed. These outputs are repeated for each species at the end of each timestep.

VI. SYNOPSIS OF ROUTINES

BFISH was constructed in modular form to facilitate program updates. This type of construction yields many function and subprogram subroutines, each isolating a separate calculational step. The relationships between the constituent routines are shown in Table 1. These routines are listed and briefly described below:

A. Main Driver

The main driver serves as the focal point for the BFISH modules. The main procedure steps through time, performing the Runge-Kutta and yield integration over each timestep. An outline of the main driver program flow appears in Figure 5.

B. Function EVAL

Function EVAL evaluates a specified function at a specified time. This function is called to calculate the values of the time dependent coefficients at specific times during the time cycle. An outline of the EVAL program flow appears in Figure 6.

C. Function PRIME

Function PRIME evaluates the first time derivative of a specified function at a specified time. This function is called to calculate the first derivatives of time dependent coefficients necessary to carry out the yield function integrations. An outline of the PRIME program flow appears in Figure 7.

Table 1.--Routine hierarchy in BFISH.

Function or program	Calls	Is called by
MAIN	DATIN READ4 SUMGRT EFFORT EVAL XGRATE RPOP RCRUIT PRIME POPDOT RSOLVE	
EVAL	POLY	MAIN EFFORT XGRATE
PRIME	POLY	MAIN
POLY		EVAL PRIME
XGRATE	EVAL RPOP	MAIN
RSOLVE		MAIN
SUMGRT		MAIN
RPOP		MAIN XGRATE
POPDOT		MAIN
RCRUIT		MAIN
EFFORT	EVAL	MAIN
DATIN	SKIP	MAIN
READ4	FIND	MAIN
FIND	SKIP	READ4
SKIP		FIND

Figure 5.--Main program outline.

- I. Initialize variables.
- II. For each timestep:
 - A. For each species:
 1. For each compartment:
 - a. Calculate XK1
 - b. Store the beginning-of-timestep commercial and sport fishing yield function values for later integration.
 2. Store the beginning-of-timestep reproduction function value for later integration.
 3. For each compartment, calculate XK2.
 4. For each compartment, calculate XK3.
 5. For each compartment:
 - a. Calculate XK4.
 - b. Calculate end-of-timestep opulation.
 6. For each compartment:
 - a. Calculate end-of-timestep commercial and sport fishing yield function values.
 - b. Integrate the commercial and sport fishing yield functions over the timestep.
 7. Calculate the end-of-timestep reproduction function value and integrate the reproduction function over the timestep.
 8. If this is the last timestep in the recruitment period, push the RSTACK array and calculate the recruitment function coefficients for next cycle.
 - B. Increment counters and zero out step totals.

Figure 6.--Function EVAL outline.

- I. Branch to the appropriate function.
- II. Branch to the appropriate type of representation.
 - A. If TYPE = 1:
 1. Evaluate the polynomial at time t.
 2. Return.
 - B. If TYPE = 2:
 1. Evaluate the function as if it were linear across the timestep.
 2. Return.

Figure 7.--Function PRIME outline.

- I. Branch to the appropriate function.
- II. Branch to the appropriate type of representation.
 - A. If TYPE = 1:
 1. Evaluate the first derivative of the polynimial at time t.
 2. Return.
 - B. If TYPE = 2.
 1. Evaluate the first derivative of the function as if the function was linear (first derivative constant) across the timestep.
 2. Return.

D. Function POLY

Function POLY evaluates an arbitrary polynomial in time given the polynomial coefficients and the time.

E. Function XGRATE

Given some arbitrary function values $f(t_1)$, $f'(t_1)$, $f(t_2)$, and $f'(t_2)$, XGRATE uses the Taylor series method described earlier to calculate and return the value of the integral:

$$\text{XGRATE} = \int_{t_1}^{t_2} f(t) dt$$

F. Subroutine RSOLVE

Subroutine RSOLVE takes the stored reproduction data for a given species and time cycle and calculates the coefficients of a polynomial in time that describes the recruitment rate to the species due to spawning activity during the stored cycle.

G. Subroutine SUMGRT

Subroutine SUMGRT calculates (see equation 1), for some specific species and time t :

$$\text{EMIGRT}_i(t) = \sum_{i \neq k} \text{XM}_{i \rightarrow k}(t)$$

$$\text{SMIGRT}_i(t) = \sum_{i \neq k} \text{XM}_{k \rightarrow i}(t) * P_k(t)$$

H. Function RPOP

Function RPOP returns the augmented population values necessary to calculate the Runge-Kutta coefficients.

I. Function POPDOT

Function POPDOT evaluates equation (1) given the necessary coefficients.

J. Function RCRUIT

For a given species, RCRUIT divides up the total recruitment rate among the various compartments.

K. Subroutine EFFORT

Subroutine EFFORT calculates and distributes the commercial fishing effort among the various compartments based upon the user selected management option. An outline of the EFFORT program flow appears in Figure 8.

L. Subroutine DATIN

Subroutine DATIN makes the initial read from the input file. An outline of the DATIN program flow appears in Figure 9.

M. Subroutine READ4

Subroutine READ4 is called to read the next four nodal points of the explicitly represented variables when they are required. An outline of the READ4 program flow appears in Figure 10.

Figure 8.--Subroutine EFFORT outline.

- I. If MOPT = 1, return.
- II. If MOPT = 2:
 - A. For each compartment:
 1. Distribute the total effort based upon the proportion of the total target population that resided in the compartment at the beginning of the last timestep.
 2. Check to see if the effort ceiling has been exceeded:
 - a. If no, continue.
 - b. If yes, set effort = ceiling and accumulate excess effort.
 - B. If excess effort ≤ 0 , or if number of iteration > 10 , return.
 - C. If excess effort > 0 and number of iterations ≤ 10 :
 1. Set total effort to be distributed = excess effort.
 2. Set total target population = the sum of the target populations in those compartments that have not reached their effort ceiling.
 3. Go back to (II.A) for next iteration.
 - D. Return.
- III. If MOPT = 3:
 - A. Sum up the total target population in those compartments that have not yet reached their yield limit.
 - B. Distribute the effort to those compartments that have not yet reached their yield limit based upon the fraction of the total target population that resided in each compartment at the beginning of the last timestep.
 - C. Return.

Figure 9.--Subroutine DATIN outline.

- I. Transfer input data to file 3.
- II. Read model structure inputs.
- III. Branch to appropriate management option inputs.
 - A. If MOPT = 1: for each compartment, read the commercial fishing effort inputs.
 - B. If MOPT = 2 or 3:
 1. Read total commercial fishing effort inputs.
 2. For each compartment, read ceiling inputs.
- IV. For each compartment, read sport fishing effort inputs.
- V. For each species:
 - A. Read reproduction coefficient inputs.
 - B. For each compartment, read commercial fishing catchability coefficient inputs.
 - C. For each compartment, read sport fishing catchability coefficient inputs.
 - D. For each compartment:
 1. Read number of compartments migrated to.
 2. For each compartment migrated to, read migration coefficient inputs.

Figure 10.--Subroutine READ4 outline.

- I. Rewind file 3.
- II. Branch to the appropriate management option inputs.
 - A. If MOPT = 1: for each compartment, read the next four nodes of the explicitly represented commercial fishing effort inputs.
 - B. If MOPT = 2 or 3:
 1. If total commercial fishing effort is explicitly represented, read the next four nodes.
 2. For each compartment, read the next four nodes of the explicitly represented ceiling inputs.
- III. For each compartment, read the next four nodes of the explicitly represented sport fishing effort inputs.
- IV. For each species:
 - A. If the reproduction coefficient is explicitly represented, read the next four nodes.
 - B. For each compartment, read the next four nodes of the explicitly represented commercial fishing catchability coefficient inputs.
 - C. For each compartment, read the next four nodes of the explicitly represented sport fishing catchability coefficient inputs.
 - D. For each compartment:
 1. Read number of compartments migrated to and type of representation for migration coefficients.
 2. If explicitly represented: for each compartment migrated to, read the next four nodes of the migration coefficient inputs.

N. Subroutine FIND

Subroutine FIND finds a specified card among the input cards for an explicitly represented variable, reads the card, and skips to the end of the card set for that variable.

O. Subroutine SKIP

Subroutine SKIP skips a specified number of cards on the input file.

VII. VARIABLE DEFINITION LIST

The following is an alphabetically arranged definition list of the major variables in the BFISH model.

B: The difference between the end-of-timestep and beginning-of timestep values of a function being evaluated in subroutine EVAL.

C (I, J, ICMPT, ISPEC):

- 1) If ICTYPE (I, ICMPT, ISPEC) = 1, C(I, J, ICMPT, ISPEC) holds the J^{th} polynomial coefficient, for species ISPEC in compartment ICMPT, for (if I = 1) the commercial fishing catchability coefficient or (if I = 2) the sport fishing catchability coefficient.
- 2) If ICTYPE (I, ICMPT, ISPEC) = 2, C(I, J, ICMPT, ISPEC) holds four nodal values (J = 3 to 6) from the input explicit representation, for species ISPEC in compartment ICMPT, for (if I = 1) the commercial fishing catchability coefficient or (if I = 2) the sport fishing catchability coefficient.

CARD: A character array (80 character capacity) used in subroutine DATIN to transfer input records from file 5 to file 3.

COEF: Used in subroutine SUMGRT to store the migration coefficient between two specified compartments at a specified time.

COEFS (I): Used in subroutines EVAL and PRIME to store the I^{th} coefficient of the specific polynomial function being evaluated.

DUMMY: An array used to transfer four nodal values of some explicitly represented variable between subroutine FIND and subroutine READ4.

E (I, J, ICMPT):

1) I = 1, MOPT = 1:

- a) IETYPE (1, ICMPT) = 1: E(1, J, ICMPT) holds the J^{th} polynomial coefficient for the commercial fishing effort function in compartment ICMPT.
- b) IETYPE (1, ICMPT) = 2: E(1, J, ICMPT) holds four nodal values ($J = 3$ to 6) from the input explicit representation for the commercial fishing effort in compartment ICMPT.

2) I = 1, MOPT = 2:

- a) ICLTYP (ICMPT) = 1: E(1, J, ICMPT) holds the polynomial coefficients ($J = 2$ to 6) for the commercial fishing effort ceiling function in compartment ICMPT. The commercial fishing effort in compartment ICMPT for the present time-step is stored in E(1, 1, ICMPT).
- b) ICLTYP (ICMPT) = 2: E(1, J, ICMPT) holds four nodal values ($J = 3$ to 6) from the input explicit representation for the commercial fishing effort ceiling in compartment ICMPT. The commercial fishing effort in compartment ICMPT for the present timestep is stored in E(1, 1, ICMPT).

- 3) $I = 1$, $MOPT = 3$: $E(1, 2, ICMPT)$ holds the yield limit per cycle for managed species in compartment ICMPT. The commercial fishing effort in compartment ICMPT for the present timestep is stored in $E(1, 1, ICMPT)$.
- 4) $I = 2$:
- a) $IETYPE(2, ICMPT) = 1$: $E(2, J, ICMPT)$ holds the J^{th} polynomial coefficient for the sport fishing effort function in compartment ICMPT.
 - b) $IETYPE(2, ICMPT) = 2$: $E(2, J, ICMPT)$ holds four nodal values ($J = 3$ to 6) from the input explicit representation for the sport fishing effort in compartment ICMPT.

EC: Commercial fishing effort.

ECDOT: First time derivative of the commercial fishing effort function.

EM: The sum of the migration coefficients out of a specific compartment.

EMIGRT (ICMPT): The sum of the migration coefficients out of compartment ICMPT.

ES: Sport fishing effort.

ESDOT: First time derivative of the sport fishing effort function.

EXCESS: Used in subroutine EFFORT (when $MOPT = 2$) to store the excess effort accumulated during one iteration that must be distributed on the next iteration.

- F1: The beginning-of-time-interval value of some function that is to be integrated.
- F1DOT: The beginning-of-time-interval first derivative of some function that is to be integrated.
- F2: The end-of-time-interval value of some function that is to be integrated.
- F2DOT: The end-of-time-interval first derivative of some function that is to be integrated.
- FP2: The estimate for the second time derivative of some function, evaluated at the beginning of a time interval, for use in a Taylor series expansion of the function across the time interval.
- FP3: The estimate for the third time derivative of some function, evaluated at the beginning of a time interval, for use in a Taylor series expansion of the function across the time interval.
- FP4: The estimate for the fourth time derivative of some function, evaluated at the beginning of a time interval, for use in a Taylor series expansion of the function across the time interval.
- FRAC (ICMPT): The fraction of the beginning-of-timestep population of a given species that resides in compartment ICMPT.
- FRACP: The fraction of the total target population that resided in a given compartment at the beginning of the previous timestep.
- H: Length of one timestep.
- IBEGIN: The nodal array location containing the beginning-of-timestep value of an explicitly represented variable.

IC: Input card (record) number.

ICARD: The input card (record) number that contains the next four nodal values for the explicitly represented variables.

ICHECK: A check to see if the number of timesteps per cycle is a multiple of four.

ICLORD (ICMPT): The order of the polynomial representing the effort ceiling in compartment ICMPT (used only if ICLTYP (ICMPT) = 1).

ICLTYP (ICMPT): 1 or 2 for polynomial of explicit representation (respectively) of the effort ceiling function for compartment ICMPT.

ICMPT: Compartment number.

ICORDR (I, ICMPT, ISPEC):

- 1) I = 1: The order of the polynomial representing the commercial fishing catchability coefficient for species ISPEC in compartment ICMPT (used only if ICTYPE (1, ICMPT, ISPEC) = 1).
- 2) I = 2: The order of the polynomial representing the sport fishing catchability coefficient of species ISPEC in compartment ICMPT (used only if ICTYPE (2, ICMPT, ISPEC) = 1).

ICOUNT: An integer counter.

ICTYPE (I, ICMPT, ISPEC):

- 1) I = 1: 1 or 2 for polynomial or explicit representation, respectively, of the commercial catchability coefficient of species ISPEC in compartment ICMPT.

- 2) I = 2: 1 or 2 for polynomial or explicit representation, respectively, of the sport fishing catchability coefficient of species ISPEC in compartment ICMPT.

IEORDR (I, ICMPT):

- 1) I = 1: The order of the polynomial representing the commercial fishing effort in compartment ICMPT (used only if IETYPE (1, ICMPT) = 1).
- 2) I = 2: The order of the polynomial representing the sport fishing effort in compartment ICMPT (used only if IETYPE (2, ICMPT) = 1).

IETYPE (I, ICMPT):

- 1) I = 1: 1 or 2 for polynomial or explicit representation, respectively, of the commercial fishing effort in compartment ICMPT.
- 2) I = 2: 1 or 2 for polynomial or explicit representation, respectively, of the sport fishing effort in compartment ICMPT.

IF: Function index: 1 or 2 for commercial fishing or sport fishing functions, respectively.

IFIRST (ISPEC): The first timestep in the recruitment period for species ISPEC.

IFUNC: Function number where

- 1 = reproduction coefficient
- 2 = recruitment rate
- 3 = commercial fishing effort
- 4 = sport fishing effort
- 5 = commercial catchability coefficient
- 6 = sport catchability coefficient
- 7 = migration coefficient
- 8 = effort or yield ceiling
- 9 = total commercial fishing effort

IGO: Branching index.

IKEY: Integer index denoting the nature of the target population for commercial fishing effort, where:

<u>IKEY</u>	<u>MAKEUP OF TARGET POPULATION</u>
1	species 1
2	species 1 + species 2
3	species 1 + species 2 + species 3

ILAST (ISPEC): The last timestep in the recruitment period for species ISPEC.

IMORDR (ICMPT, ITO, ISPEC): Order of the polynomial used to represent the migration coefficient for species ISPEC from compartment ICMPT to compartment MCMPT (ICMPT, ITO, ISPEC) (used only if IMTYPE (ICMPT, ISPEC) = 1).

IMTYPE (ICMPT, ISPEC): 1 or 2 for polynomial or explicit representation, respectively, of the migration coefficient(s) for species ISPEC leaving compartment ICMPT.

IRCRUT (ISPEC): = 1 if the present timestep is part of the recruitment period for species ISPEC; = 0 otherwise.

IREAD: The timestep number before which the next four nodal values for explicitly represented variables must be read.

IRFLAG: = 0 if no variable is explicitly represented; = 1 otherwise.

IRORDR (I, ISPEC):

1) I = 1: The order of the polynomial describing the reproduction coefficient for species ISPEC (used only if IRTYPE (I, ISPEC) = 1).

2) I = 2: The order of the polynomial describing the recruitment rate for species ISPEC (will always = 4).

IRP1: A counter usually equal to the number of coefficients in a polynomial.

IRTYPE (I, ISPEC):

1) I = 1: 1 or 2 for polynomial or explicit representation, respectively, of the reproduction coefficient for species ISPEC.

2) I = 2: 1 always since the recruitment rate for species ISPEC is always generated by BFISH as a polynomial.

IS: An integer counter.

ISKIP: An integer argument equal to the number of cards (records) that are to be skipped on the input file.

ISPEC: Species number.

ISTEP: Timestep number.

ISTOP: Integer variable = MATURE (ISPEC).

IT: Integer variable indexing a compartment migrated to.

ITER: Iteration number.

ITO: Integer counter indexing a compartment migrated to.

ITORDR: The order of the polynomial representing the total commercial fishing effort (used only if ITTYPE = 1).

ITST: An array of timestep numbers.

ITTYPE: 1 or 2 for polynomial or explicit representation, respectively, of total commercial fishing effort.

IYKEY: Integer index denoting the species to which the yield limit applies (used only if MOPT = 3), where:

<u>IYKEY</u>	<u>YIELD LIMIT APPLIES TO</u>
1	species 1
2	species 1 + species 2
3	species 1 + species 2 + species 3
4	species 2 + species 3

MATURE (ISPEC): Age (in cycles) at which members of species ISPEC enter the fishery.

MCMPT (ICMPT, ITO, ISPEC): Compartment numbers to which members of species ISPEC migrate from compartment ICMPT (ITO = 1, MTO (ICMPT, ISPEC))

MFLAG (ICMPT): = 1 if compartment ICMPT is in the management area;
= 0 otherwise.

MOPT: Management option, where

<u>MOPT</u>	<u>DESCRIPTION</u>
1	externally (user) supplied commercial fishing effort
2	commercial fishing effort internally generated subject to user supplied effort ceilings
3	commercial fishing effort internally generated subject to user supplied yield limits

MTO (ICMPT, ISPEC): The number of different compartments migrated to from compartment ICMPT by species ISPEC.

NCARD: The number of input cards (records) necessary to explicitly represent each node in a time cycle. Hence, each explicitly represented variable (TYPE = 2) will have a set of NCARD input records associated with it.

NCMPT: The number of compartments being modeled in the present analysis.

NCYCLE: The number of time cycles being modeled in the present analysis.

NLAST: The array location holding the last node of the set of explicit nodal values currently in storage.

NMAX: The total number of timesteps that will be modeled during the present analysis.

NMCMPT: The number of managed compartments being modeled in the present analysis.

NORDER: Order of a polynomial being evaluated.

NSPEC: The number of species being modeled in the present analysis.

NSTEP: Number of timesteps per cycle.

NUMBER: An integer variable usually used to store the value of MTO (ICMPT, ISPEC).

- P: Population.
- PDOT: First time derivative of the population of a given species in a given compartment.
- PDOTOT: The sum of PDOT over all compartments.
- PMANAG: The sum of the populations of a given species over all managed compartments.
- POP (ICMPT, ISPEC): Population of species ISPEC in compartment ICMPT.
- PTARGET (ICMPT): The target population in compartment ICMPT.
- PTOT (ISPEC): The population of species ISPEC summed over all compartments.
- QC: Commercial fishing catchability coefficient.
- QCDOT: First time derivative of the commercial fishing catchability coefficient.
- QS: Sport fishing catchability coefficient.
- QSDOT: First time derivative of the sport fishing catchability coefficient.
- R (I, J, ISPEC):
- 1) I = 1: R(1, J, ISPEC) holds either the polynomial coefficients (in J = 1 to 6) or nodal values (in J = 3 to 6), for IRTYPE (1, ISPEC) = 1 or 2 respectively, for the reproduction coefficient for species ISPEC.
 - 2) I = 2: R(2, J, ISPEC) holds the polynomial coefficients (J = 1 to 5) for the 4th order polynomial describing the recruitment rate to species ISPEC.
- R1: Beginning of timestep value of the reproduction function.

R1DOT: Beginning of timestep value of the first time derivative of the reproduction function.

RBAR (ISPEC): The integral of the reproduction function for species ISPEC over the recruitment period.

RC: Recruitment rate.

RDSAVE (ISPEC): Beginning of recruitment period value of the first time derivative of the reproduction function for species ISPEC.

RP: Reproduction coefficient.

RPDOT: First time derivative of the reproduction function.

RSAVE (ISPEC): Beginning of recruitment period value of the reproduction function for species ISPEC.

RSTACK (J, K, ISPEC): The stack of values used to calculate the recruitment coefficients for species ISPEC.

$K (= 1 \text{ to } \text{MATURE}(\text{ISPEC})) =$ the number of cycles previous to the current cycle that the stored values represent.

$J (= 1 \text{ to } 5) =$

<u>J</u>	<u>DESCRIPTION</u>
1	$f(t_1)$
2	$\dot{f}(t_1)$
3	$f(t_2)$
4	$\dot{f}(t_2)$
5	$\int_{t_1}^{t_2} f \, dt$

where

$$f(t) = RP(t) * P_{TOTAL}(t)$$

RP(t) = reproduction coefficient for species ISPEC at
time t

P_{TOTAL}(t) = total population (summed over all compartments)
for species ISPEC at time t

$$\dot{f}(t) = \frac{df}{dt} \text{ evaluated at time } t$$

The recruitment coefficients for species ISPEC in any cycle are calculated from a Taylor series expansion whose parameters are calculated from the 5 stored values RSTACK (J, MATURE(ISPEC), ISPEC), J = 1 to 5.

RTOT: Total recruitment rate for a specific species.

S(ICMPT): The Collatz sensitivity coefficient for the Runge-Kutta calculations for compartment ICMPT for a specific species.

SMIGRT (ICMPT): For a specific species, the sum of the products of the migration coefficients into compartment ICMPT and the populations of the contributing compartments, or

$$SMIGRT(i) = \sum_{i \neq j} XM_{j \rightarrow i} * P_j$$

$XM_{j \rightarrow i}$ = migration coefficient from compartment j to
compartment i for a specified species and time.

P_j = population in compartment j of a specified species
at a specified time.

STAR: An alphabetic variable (= *) used to denote the end of the input file.

SUM: = SMIGRT (ICMPT), used as a function subroutine argument.

T: Time.

TE(J):

- 1) If ITTYPE = 1, TE(J) holds the J^{th} polynomial coefficient for the total commercial fishing effort function.
- 2) If ITTYPE = 2, TE(J) holds four nodal values ($J = 3$ to 6) from the input explicit representation of the total commercial fishing effort.

TEFORT: Total commercial fishing effort.

TIME(J):

- 1) $J = 1$: beginning of timestep time
- 2) $J = 2$: middle of timestep time
- 3) $J = 3$: end of timestep time

TT: The total target fish population summed over compartments that have not yet reached their effort ceiling limit.

TTARGET: The total target fish population.

TTOTAL: Total time expired.

XK1 (ICMPT): First Runge-Kutta coefficient for compartment ICMPT and a specific species.

XK2 (ICMPT): Second Runge-Kutta coefficient for compartment ICMPT and a specific species.

XK3 (ICMPT): Third Runge-Kutta coefficient for compartment ICMPT and a specific species.

XK4 (ICMPT): Fourth Runge-Kutta coefficient for compartment ICMPT and a specific species.

XM (J, ICMPT, ITO, ISPEC):

- 1) If IMTYPE (ICMPT, ISPEC) = 1, XM (J, ICMPT, ITO, ISPEC) holds the J^{th} polynomial coefficient for the migration coefficient for migration of species ISPEC from compartment ICMPT to compartment MCMPT (ICMPT, ITO, ISPEC).
- 2) If IMTYPE (J, ICMPT, ITO, ISPEC) = 2, XM (J, ICMPT, ITO, ISPEC) holds from nodal values ($J = 3$ to 6) from the input explicit representation of the migration coefficient for migration of species ISPEC from compartment ICMPT to compartment MCMPT (ICMPT, ITO, ISPEC).

XNMORT (ISPEC): Natural mortality coefficient for species ISPEC.

XPOLY: Storage variable for a partially evaluated polynomial used in function subroutine POLY.

Y1: Used in subroutine EVAL to denote the beginning-of-timestep value of a function.

Y2: Used in subroutine EVAL to denote the end-of-timestep value of a function.

YCl (ICMPT): The commercial yield function for compartment ICMPT evaluated at the beginning of the timestep.

YClDOT (ICMPT): The first time derivative of the commercial yield function for compartment ICMPT evaluated at the beginning of the timestep.

YCMNG: Commercial fishing yield in the management area over a one timestep period.

- YCMTOT (ISPEC): Cycle-to-date commercial fishing yield in the management area of species ISPEC.
- YCSTEP (ISPEC): Total commercial fishing yield (summed over all compartments) of species ISPEC over a one timestep period.
- YCTOT (ISPEC): Total cycle-to-date commercial fishing yield (summed over all compartments) of species ISPEC.
- YIELD C: Commercial fishing yield.
- YIELDS: Sport fishing yield.
- YMANAG (ICMPT): Cycle-to-date yield of managed species in compartment ICMPT.
- YS1 (ICMPT): The sport yield function for compartment ICMPT evaluated at the beginning of the timestep.
- YS1DOT (ICMPT): The first time derivative of the sport yield function for compartment ICMPT evaluated at the beginning of the timestep.
- YSMNG: The sport fishing yield in the management area over a one timestep period.
- YSMTOT (ISPEC): Cycle-to-date sport fishing yield in the management area of species ISPEC.
- YSSTEP (ISPEC): Total sport fishing yield (summed over all compartments) of species ISPEC over a one timestep period.
- YSTOT (ISPEC): Total cycle-to-date sport fishing yield (summed over all compartments) of species ISPEC.
- Z: Multiplier (= 0., 0.5, or 1.) used in subroutine EVAL when evaluating explicitly represented functions.

VIII. NOTES

A. BFISH backspaces, rewinds, and rereads the input file repeatedly during execution. This may cause laughter in the control room if the input unit happens to be a card reader. To avoid this, BFISH writes the entire input file to disc before starting its reads. To facilitate this, the user must make a disc file with logical unit number 3 available to the program before the execution step.

B. Increasing the number of species and compartments that may be modeled is as simple as increasing the dimensions of the appropriate arrays in the common blocks.

C. If you elect to use polynomials to represent any of the time dependent coefficients, be sure that you know what you are doing. At no time should any of the coefficients be negative. The BFISH program will be quite happy with negative coefficients, but the user may not be as content with the results of the analysis if fish migrate backwards or fishing fleets supplement the population by throwing fish into the water.

This non-negativity criterion holds, of course, for explicit representation (type 2) as well. But in this case the user can easily inspect the inputs for negative values.

A good personal rule would be to inspect a plot of each of your input polynomials before using it.

D. Note that with $MOPT = 2$ or 3 , the effort is distributed as per the distribution of the target population at the beginning of the previous timestep, and then held constant over the present timestep. Therefore, the printout at time t shows the effort as calculated at $(t - H)$, which is based upon the population distribution at $(t - 2H)$.

E. While it is not necessary, it would certainly be intuitively pleasing if the end-of-cycle coefficient values = the beginning-of-cycle values ($f(t_F) = f(0)$). This is done by BFISH for explicit variables, but is up to the user for polynomials.

